EFFECT OF DUCTS ON THE ATTENUATION OF NEUTRONS AND GAMMA RAYS IN THE M.I.T. CYCLOTRON SHIELD

by

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I. INTRODUCTION

Fundamental knowledge of the interactions of neutrons and gamma rays with matter is essential for an understanding of nuclear shielding. Most shielding studies have been concerned with the attenuation of radiations by materials in bulk. Little work, however, has been done on the effects of ducts and other openings in shields. Nearly every shield must be perforated to some degree, and leakage through such openings may constitute the major uncertainty in the shield design. The M.I.T. cyclotron has recently been relocated inside a concrete shield. A large movable section of this wall provides access to the inside of the cyclotron vault. The partially elevated door provides a convenient platform on which materials can be arranged for test purposes.

In the present work concrete blocks containing six-inch ducts were used. The effects of ducts on the neutron and gamma ray attenuations in the shield were investigated. The practical results of such a study assist in determining the optimum shape and position of openings and voids in shields. The particular experimental arrangement which we have used at the M.I.T. cyclotron provides data of direct value in the theoretical understanding of ducts. The use of water tanks in

place of concrete should allow for greater flexibility in experiments of this type. The major uncertainty is in the energy spectrum of the radiation. Further work on this problem is in progress.

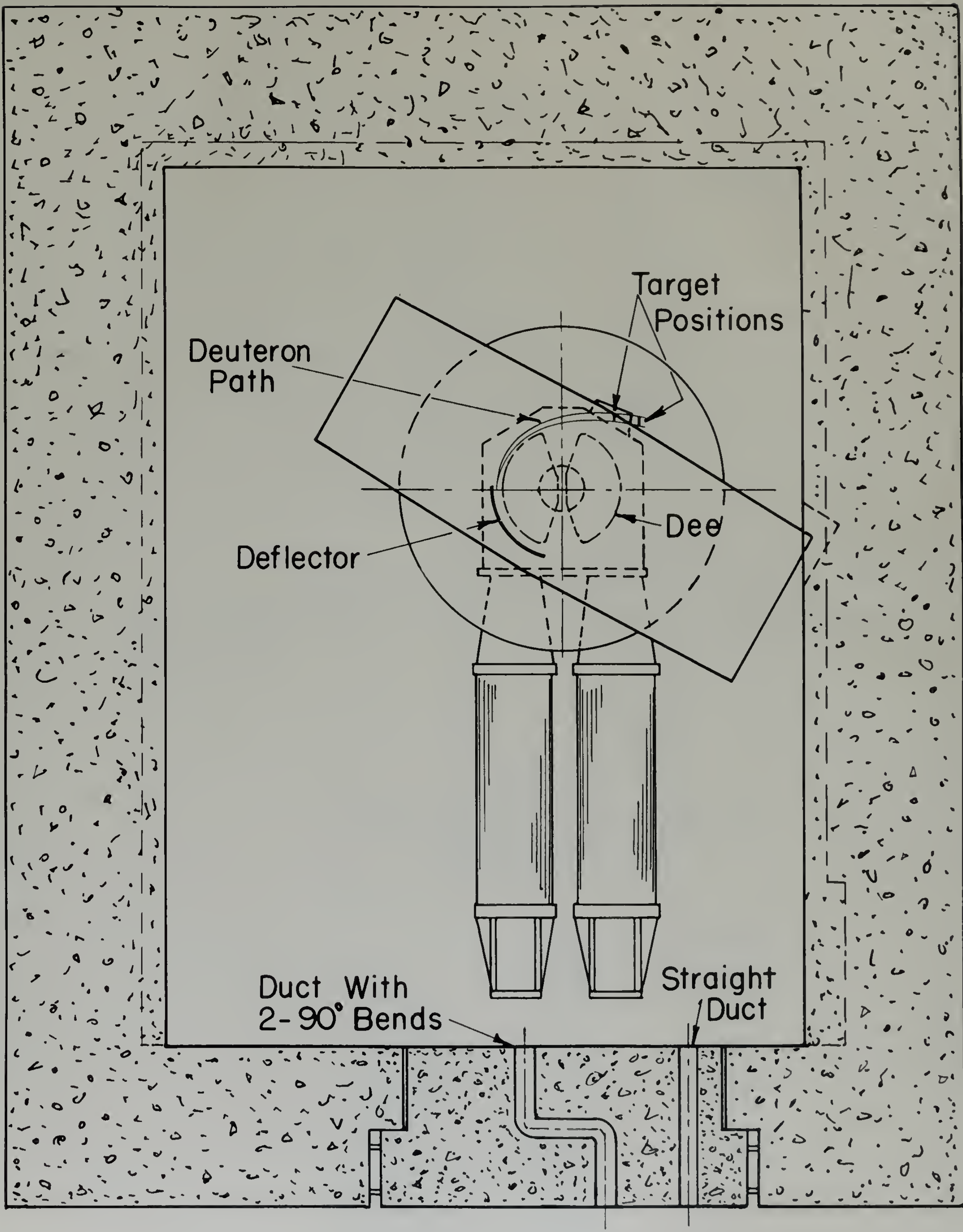
II. EXPERIMENTAL ARRANGEMENT AND PROCEDURES

Description of Cyclotron Shield and Door

The M.I.T. cyclotron is installed in a room whose principal interior dimensions are 22' by 16' by 12'. It is shielded by ordinary concrete of thickness four feet on each of four sides and three feet on top. The general arrangement is as shown in Figure 1.

Access to the interior is by an opening in the shield 8'6" high. This opening is eight feet wide at the inside of the shield, nine feet wide at the outside. It is closed by a concrete door four feet thick, which is lifted vertically into position from a recess in the floor by hydraulic power. The step in its horizontal cross section at the mid-point prevents the straight-through penetration of radiation at the door's edge.

The concrete mix used in the fabrication of the cyclotron shield was prepared by the Boston Sand and Gravel Company using one part by weight[6] Type II Portland cement, two parts sand, and four parts gravel (1" grated to 1/4"). The chemical analysis of the cement on a weight basis is given in Table I.



Figure– 1

Plan View Of Cyclotron And Shield Showing Position Of Ducts

TABLE I

CaO	63.3% (est.)
SiO_2	22.2%
Al_2O_3	5.1%
Fe_2O_3	4.9%
MgO	1.4%
SO_3	1.5%
Misc.	1.6%

An estimate of the composition of the sand and gravel used is based on its origin and given in Table II.

TABLE II

Sand and Gravel Composition
in Cyclotron Wall
(weight basis)

	Sand	Gravel
SiO_2	95.87%	73.60%
Al_2O_3	1.83%	14.44%
Fe_2O_3	0.04%	0.43%
FeO	0.27%	1.49%
CaO	0.25%	1.04%
Na_2O	0.88%	4.20%
K_2O	0.61%	4.46%
H_2O	trace	trace

An analysis of the concrete by Oak Ridge National Laboratory indicated a water content of 7.6% by weight. From the foregoing, the cyclotron wall has an average composition as given in Table III.

TABLE III

Average Composition of Concrete
in Cyclotron Wall
(weight basis)

H	0.84
O	50.88
Si	31.4
Al	4.65
Ca	6.42
Fe	1.29
Mg	0.11
Na	1.82
K	2.09
S	0.08
Misc.	0.33

Description of Neutron Source

The reaction $Be^9(d,n)B^{10}$ provides an intense source of fast neutrons and energetic gamma rays. The neutron spectrum from this source has been investigated both theoretically and experimentally by Cohen[7] using 14-Mev deuterons (see Figure 2). Since the deuterons incident on the beryllium in the present experiments were approximately 15 Mev in energy, the resulting neutron spectrum should be very similar to that determined by Cohen.

In interpreting the results of these experiments, however, it is desirable to know the spectrum and distribution of neutrons at the entrance to the ducts. As shown in Figure 1, the duct entrances are oriented approximately 90° to the direction of the deuteron beam at the target. Obviously the neutron intensity is greatest in the forward direction. Roberts and Abelson[9] found five to twenty times as many neutrons at 0° to the deuteron beam as at 90° using Au, Cu, Al, and C targets, and Cu, Ag, Al, and Mn detectors. Recent experiments by Falk, Seitz, and Creutz[8] using the $Be^9(d,n)B^{10}$ reaction show a half-width of 26 degrees for the intensity of the emergent neutron cone as determined by Ag detectors (6-Mev threshold) and of 31 degrees as determined by Cu detectors (12.5-Mev threshold).

From the foregoing, it would be expected that

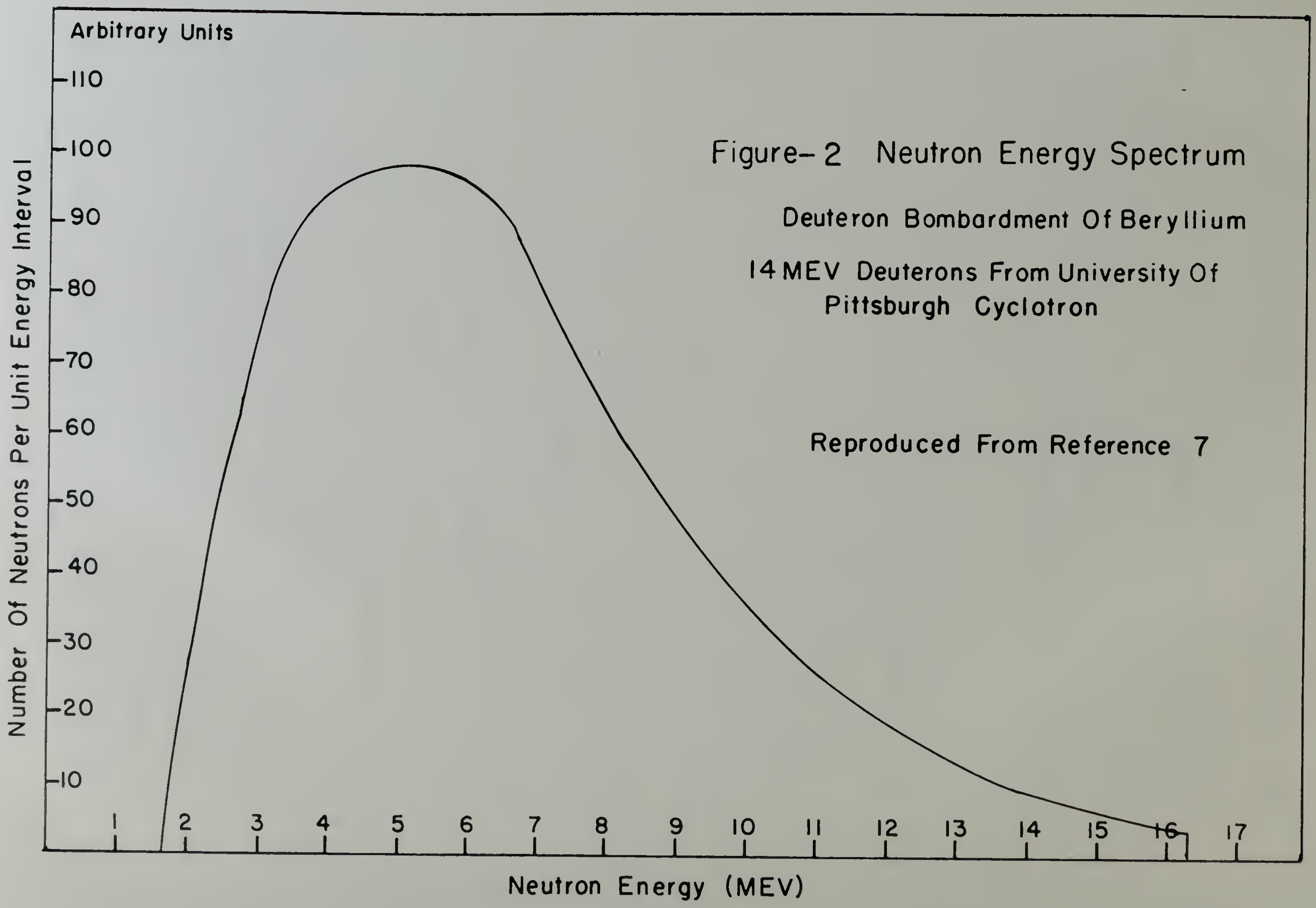


Figure- 2 Neutron Energy Spectrum

Deuteron Bombardment Of Beryllium

14 MEV Deuterons From University Of Pittsburgh Cyclotron

Reproduced From Reference 7

a small percentage of the neutrons produced at the target would be directed toward the ducts. Such neutrons must penetrate a minimum of eight inches of scattering material (brass) in the cyclotron vacuum chamber, dees, and resonant lines. The probability that a neutron from the target would not be scattered before reaching the duct is $\lesssim .02$.

Insofar as it affects the neutron spectrum and the angular distribution at the duct entrances, it is important to distinguish between neutrons produced at the target and elsewhere. Since only 10 to 25 per cent of the resonant ion beam reaches the target, a diffuse source of neutrons will be produced in the copper of the dee structure and in the tungsten septum.

As a first approximation in these experiments, the cyclotron vault may be considered as a diffuse source of neutrons. To test this hypothesis, the concrete blocks were rearranged to reposition the straight duct as shown in Figure 5. The neutron attenuations for both positions (see Figure 9) are nearly identical over most of the duct length. The results tend to support this approximation. It appears that the source of neutrons was sufficiently constant over the inner face of the concrete blocks to allow without correction a comparison between ducts of different shapes located at small distances from one another in the front door of the cyclotron shield.

Description of the Ducts

The design and arrangement of the cyclotron door is such that it can be conveniently adapted to an experimental study of the problem under investigation. By lowering the cyclotron door, an opening can be made in the shield at its top. By filling this opening with concrete blocks containing ducts of a selected size, an effective substitute can be made for the actual penetration of the shield itself.

A set of concrete blocks was designed whose overall dimensions in a horizontal plane were identical with those of the horizontal cross section of the door. The primary considerations governing their thickness were the size and conformation of ducts to be studied, the allowable overload on the hydraulic hoisting system, and the desirability of separating the ducts from discontinuities in the shielding medium. In order to accommodate counter tubes and their associated equipment, and, in addition, to obtain a sectional area of duct large compared to the area of foils used for detection, a duct diameter of six inches was selected. A 1/8-inch thick steel plate on top of the cyclotron door made it desirable to separate the outer edge of the duct from this discontinuity by at least nine inches. Giving consideration to the allowable overload on the hydraulic

hoisting system for the door, it was considered desirable to limit the overload to between four and five tons. A total block thickness of twenty-four inches and overall weight of about 4.4 tons were accordingly chosen. The only difficulty experienced as a result was the limitation thereby imposed on the conformation of the helical duct.

For convenience in handling, the weight was divided between eight blocks. The interfaces between blocks were offset to prevent the straight-through penetration of neutrons and gamma rays in the openings between blocks. Considerable care was taken in manufacture to obtain smooth square faces both to minimize such penetration and to maintain the shielding medium as uniform as possible. The effects of such discontinuities were further reduced by locating the ducts as far as possible from them. Reinforcing material was not used in order completely to avoid any effects of the nuclear reactions that would result from its use.

First consideration was given to a duct with two right-angle bends as shown in Figure 3. It was thought desirable to penetrate the shield by displacing two sections of a straight duct and joining those sections with an intermediate section normal to both. In an attempt to keep as much shielding material as possible in line with each of the displaced sections, they

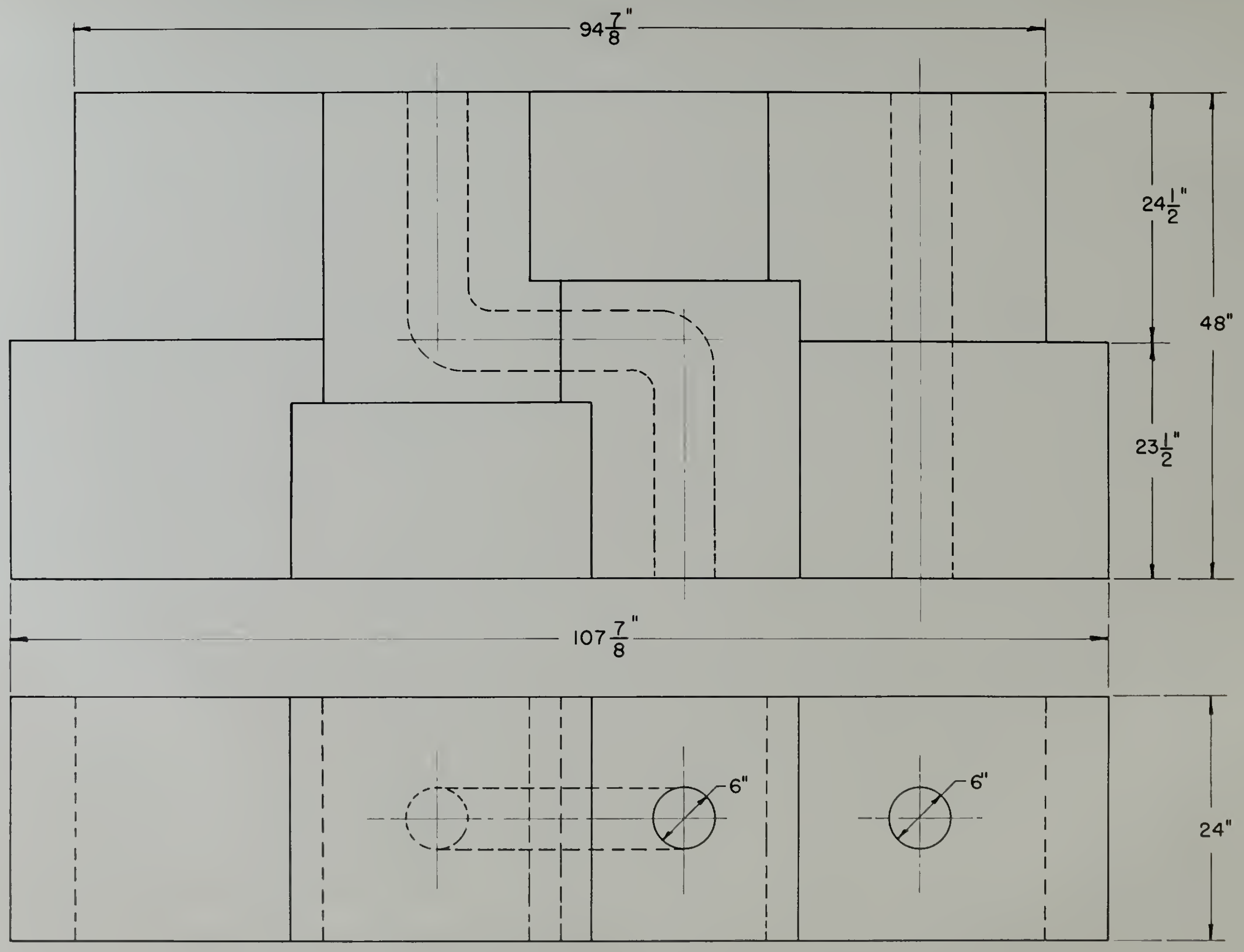


Figure- 3

Straight & Bent Ducts Through Concrete Blocks
In Cyclotron Shield

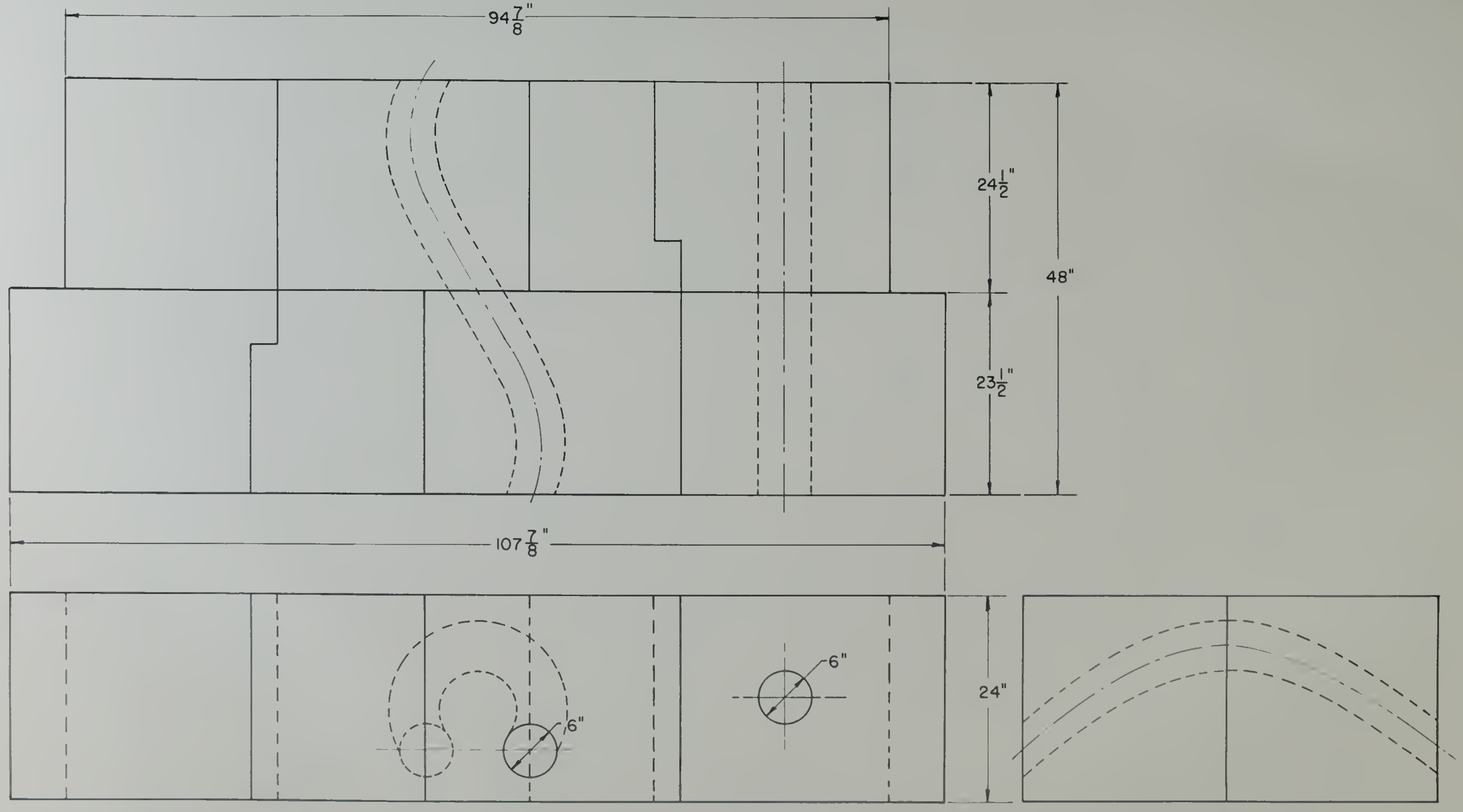


Figure - 4

Straight & Helical Ducts Through Concrete Blocks
In Cyclotron Shield

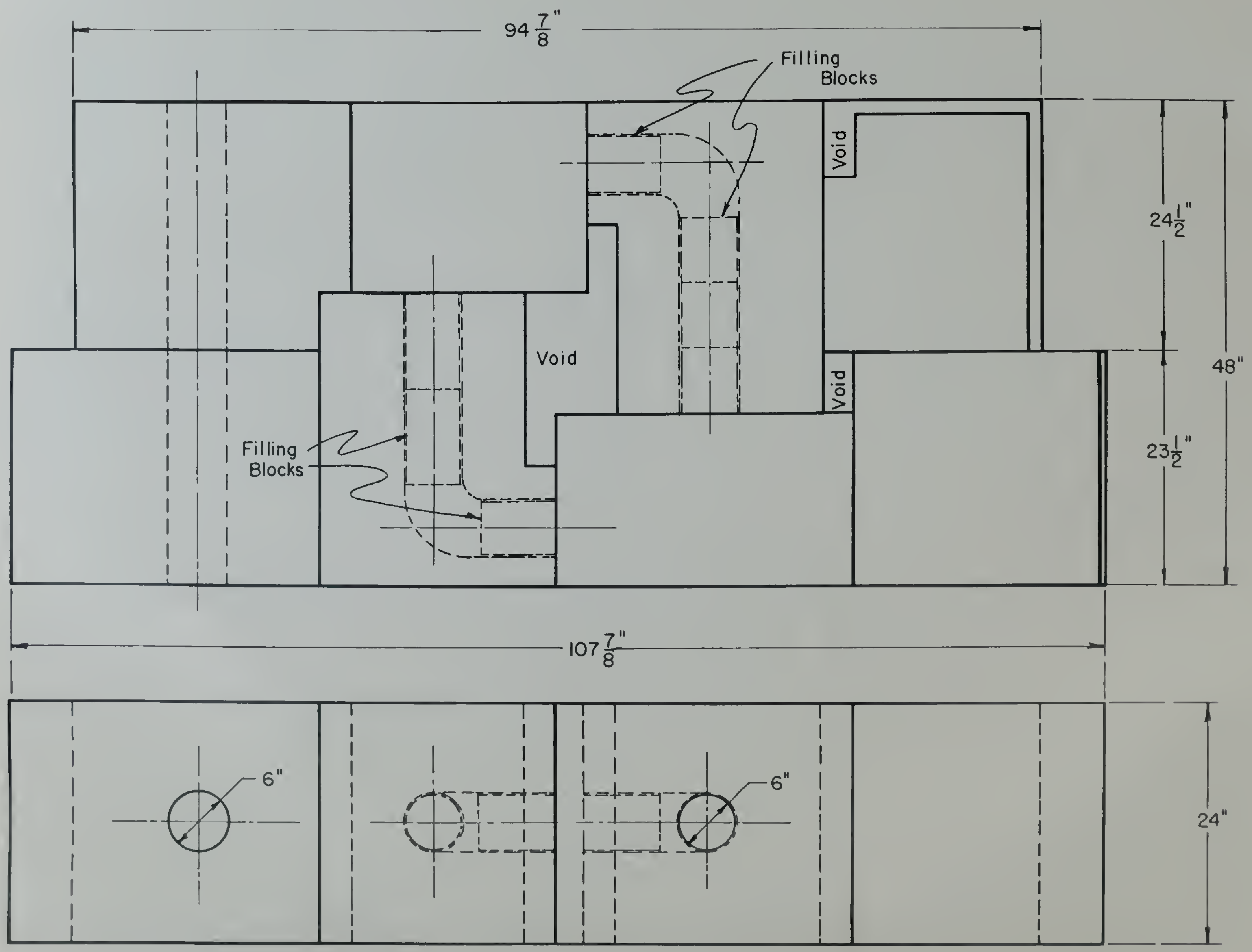


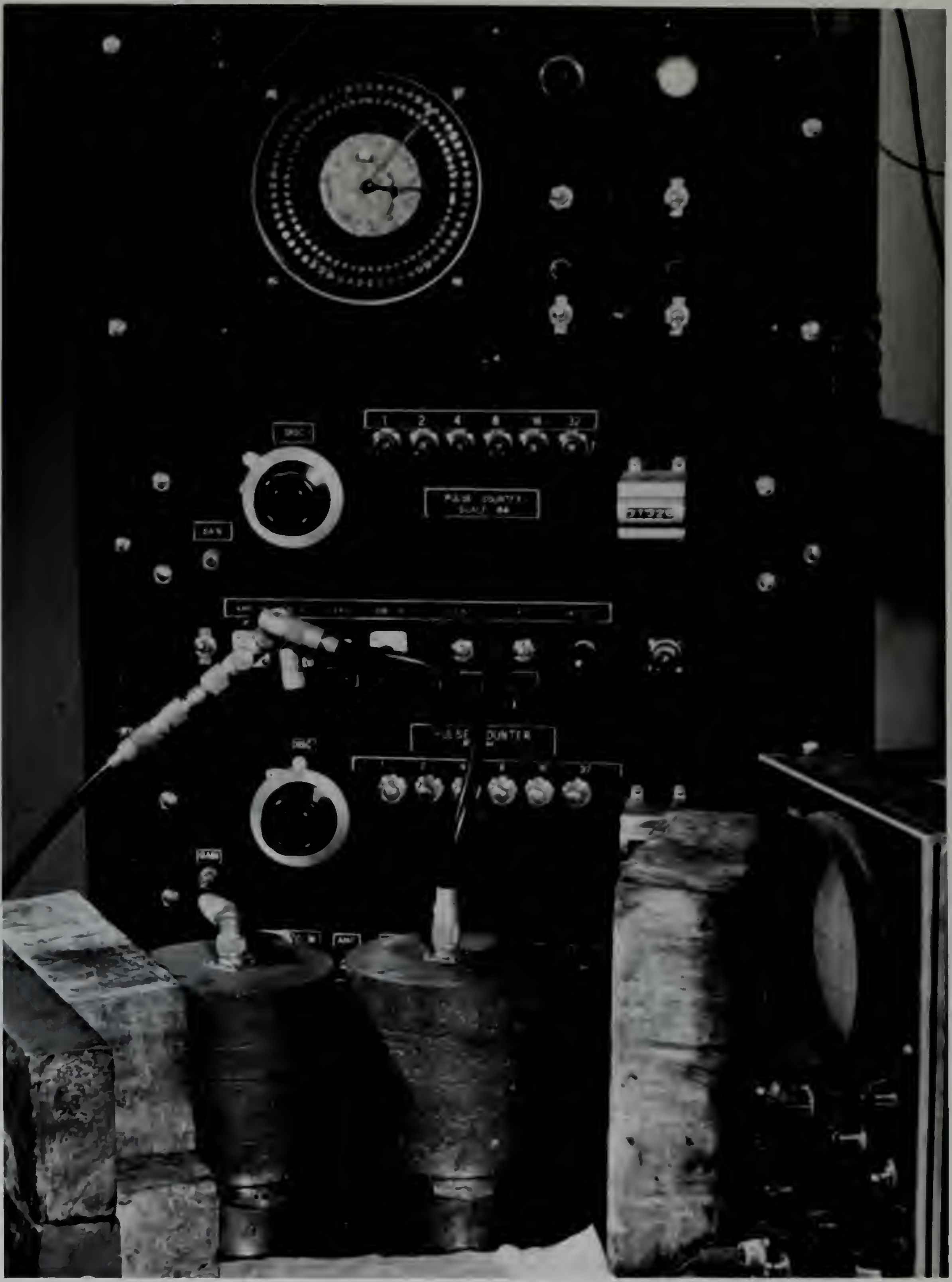
Figure-5
Alternate Location Of Straight Duct Through Blocks
In Cyclotron Shield

were made equal in length. It seemed probable, moreover, that a duct would be effective if the amount of material removed in straight lines along the duct axis were kept continuously small. A duct was accordingly designed whose center line was a helix of helical angle 270°. It was necessary to restrict the angle to this value as a maximum in order to prevent the duct from closing on a line normal to the inner face of the shield at the duct entrance.

To compare accurately the attenuations obtained in each duct, it was necessary that they either be tested under identical conditions of cyclotron operation (an impossibility) or that they be referred to some standard. Moreover, it seemed important to investigate the properties of a straight duct. Hence, the blocks were designed to include such a duct for basic study. At the same time measurements made on the straight duct were used for normalization of the measurement on other ducts.

Certain of the investigations required that the ducts be closed in whole or in part. Concrete plugs of varying lengths were therefore fabricated as shown in Figure 7.

The composition of the concrete plugs was that of the concrete blocks. A recess was provided at one end of each block for the insertion of foils and foil holders. The variable length of the plugs made it possible



gure 6. Counters, scalers, and timer.

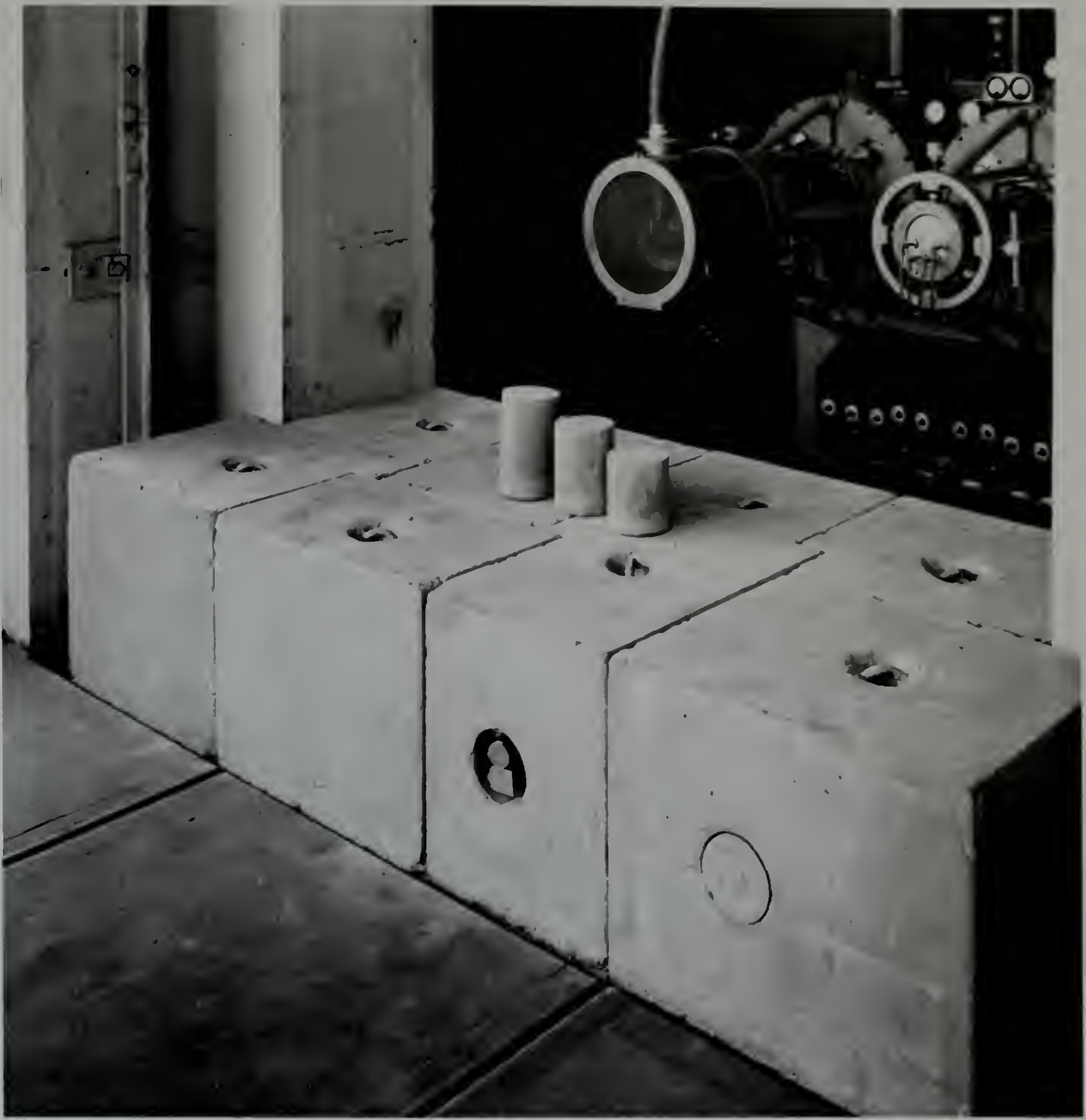


Figure 7. Blocks in place on lowered cyclotron door with cyclotron in background. Note foil holders in exit of bent duct and concrete plugs in position in exit of straight duct. Extra concrete plugs are shown on top of the blocks.

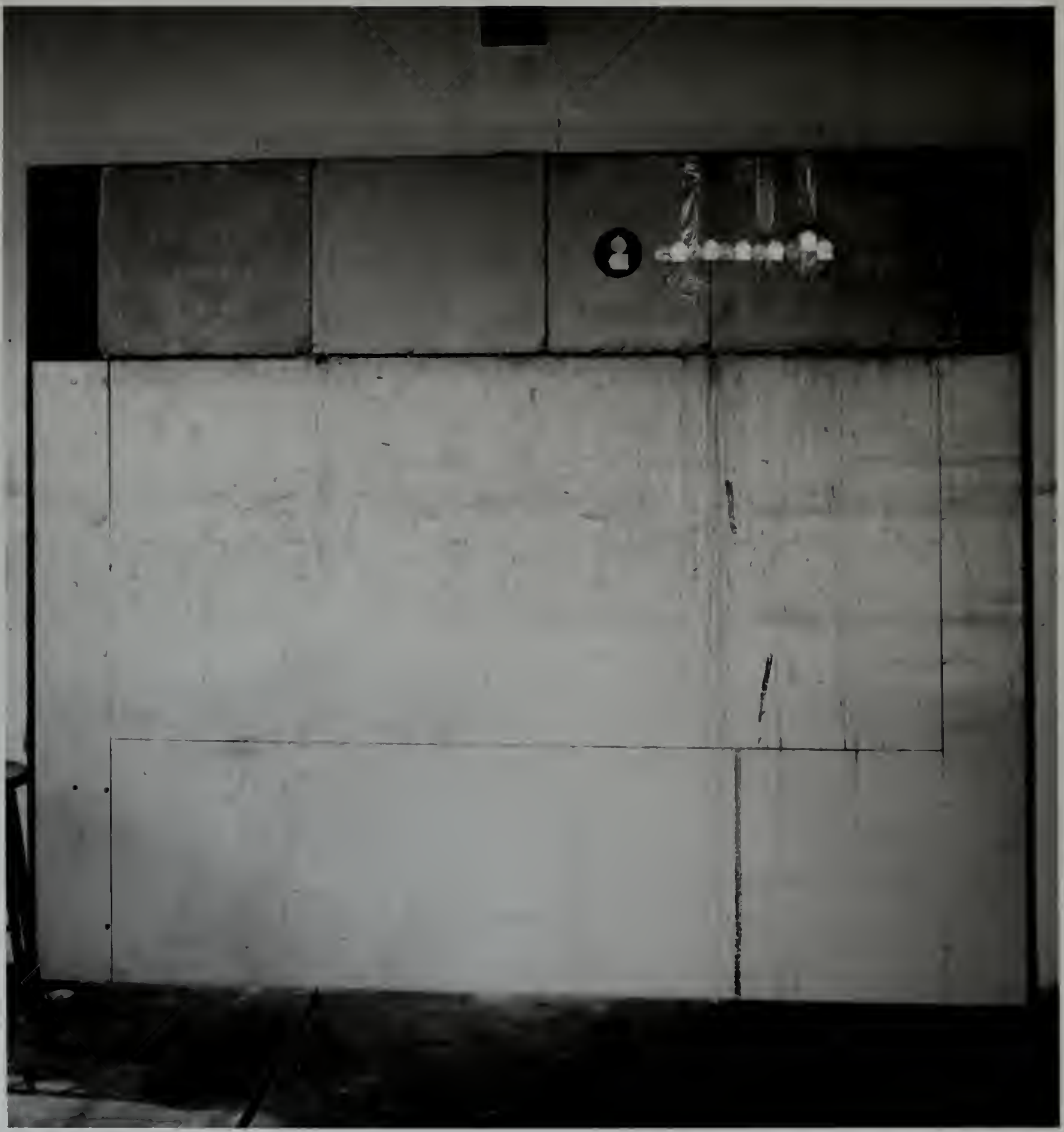


Figure 8. View showing blocks in position and cyclotron door in the elevated position. Note arrangement of foils for measurement of radial distribution around outlet from straight duct.

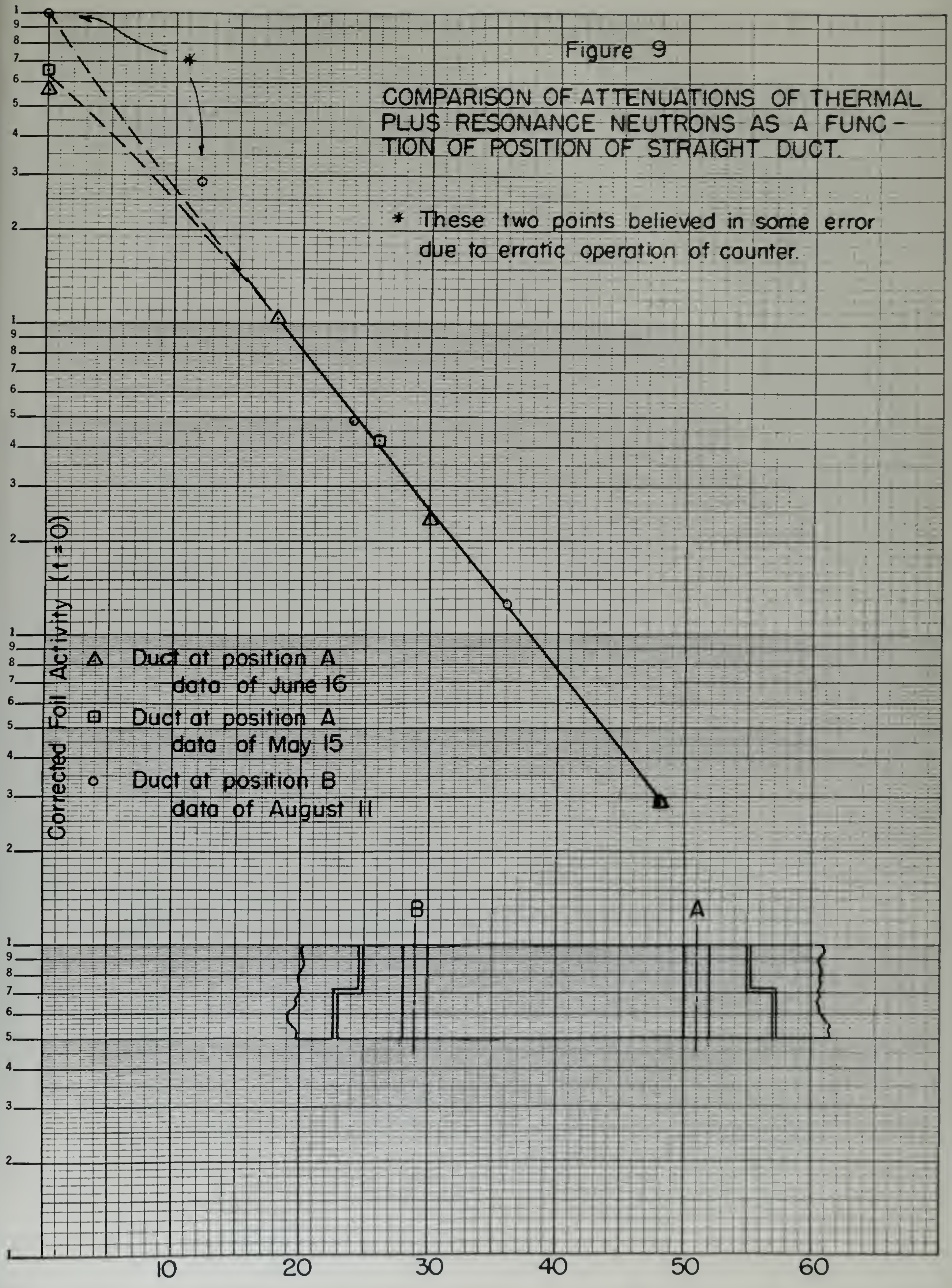


Figure 9

COMPARISON OF ATTENUATIONS OF THERMAL PLUS RESONANCE NEUTRONS AS A FUNCTION OF POSITION OF STRAIGHT DUCT.

* These two points believed in some error due to erratic operation of counter.

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to change both the position and length of voids in the blocks.

Neutron Detection Methods

If a thin foil of thickness T and area A containing N nuclei of absorption cross section $\sigma(E)$ at neutron energy E per unit volume is placed in a neutron flux nv(E), the number of neutrons absorbed per second is given by

$$Q = A \int_{E_{min}}^{E_{max}} nv(E) \left[1 - e^{-NT\sigma(E)} \right] dE. \qquad (1)$$

If the foil is exposed in the flux for a time t_e and has an activity of mean life τ, the radioactivity produced will be given by

$$R_e = Q\,(1 - e^{t_e/\tau}) \text{ disintegrations per second second.} \qquad (2)$$

Furthermore, if the detector has a cross section which varies as 1/v,

$$Q = A \int n\,dE. \qquad (3)$$

Many elements, including indium^{115}, exhibit a 1/v change in cross section and therefore are activated in accordance with equation (3). In^{115} has a cross section of about 100 barns at 0.1 ev which increases as 1/v for decreasing energies (54-minute beta activity). In addition, it has a high (26,400 barns) and narrow resonance

at 1.44 ev. Cadmium has an absorption cross section of 7800 barns at 0.18 ev which drops sharply above this energy. The result of enclosing an indium foil in cadmium (~1 mm thick) is that essentially all the thermal neutrons are absorbed in cadmium. If two equal indium foils are simultaneously irradiated in a neutron flux, one encased in a cadmium holder and one encased in an aluminum holder which is essentially transparent to neutrons of all energies, the activity of the foil in the cadmium holder will be proportional to the 1.44-ev flux (indium resonance neutrons) and the activity of the foil in the aluminum holder will be proportional to the total flux 1.44 ev plus thermals. Simple subtraction of the two activities gives an activity proportional to thermal flux alone.

This cadmium-difference method was used to detect neutrons in the low energy range. Indium has two stable isotopes, In^{115}, which constitutes 95.5 per cent of the natural element, and In^{113}, which constitutes the remaining 4.5 per cent. Neutron capture in In^{113} leads to two beta activities with half-lives of 48 days and 72 seconds, neither of which was significant for our measurements due to the half-lives involved and the small percentage of the isotope present. Neutron capture in In^{115} leads to the 54-minute activity mentioned above and also to a 13-second activity; the latter was made

negligible in those experiments by allowing at least three minutes to elapse before counting began. In^{115} may also be excited by an inelastic scattering process to a metastable level at 340 kev, returning to the ground state by a strongly internally-converted gamma transition of 4.5-hour half-life. The threshold for this excitation is about 1 Mev and the cross section is about 0.36 barn. Based on the experiments of Tittle[1], Faul and Farmer[2], it is concluded that this activity is negligible in the present experiments.

The presence of a foil leads to a perturbation of the neutron flux. Bothe[3] derived the following foil drain factor for discs:

$$f = \frac{1}{1 + \frac{\alpha}{2}\left(\frac{R_K}{\lambda_s} \cdot \frac{3L}{2R_K + 3L} - 1\right)} \qquad (4)$$

$$\alpha = 1 - e^{-\mu\delta}(1 - \mu\delta) + \mu^2\delta^2 E_i(-\mu\delta) \qquad (5)$$

where α = average absorption probability for any neutron striking the foil;

δ = thickness of the foil;

μ = reciprocal of the mean free path in the foil;

E_i = logarithmic energy interval;

R_K = radius of the foil;

λ_s = scattering mean free path of the medium surrounding the foil;

L = diffusion length for neutrons in the medium surrounding the foil.

For foils completely surrounded by concrete the drain correction used was 1/1.0102. Due to the large scattering mean free path in air, f is negligible for foils located within ducts. No drain corrections were made for such foils.

A correction for the attenuation of the cadmium holders must be made because of the appreciable cross section for 1.44-ev neutrons (11.5 barns). This correction has been calculated by means of equation (5) as 1.11 for 1-mm cadmium holders. Dacey, Paine, and Goodman[5] investigated this correction experimentally and obtained a cadmium attenuation factor for resonance neutrons of 1.12. A correction of 1.11 was used in all computations in this work.

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Neutron fluxes in the high energy region were obtained by threshold detection, a crude method of neutron spectroscopy which makes use of varying thresholds for activation by high energy neutrons. The predominant factor in determining the actual threshold energy for neutron activation is the probability function for penetration of the coulomb barrier by the proton or alpha particle which must be expelled to produce a radioactive daughter. Bethe[4] derived a penetrability function showing that the probability of escape of a charged particle from a nucleus is

$$P = \exp\left[-2g\,\gamma\,\left(\frac{E'}{B}\right)\right] ; \qquad (6)$$

where

$$g = \left[\frac{2aA}{a + A}\, z\, Z\, e^2\, R\right]^{1/2} ;$$

$$\gamma(x) = \left[x^{-1/2} \operatorname{arc\,cos} x^{1/2} - (1 - x)^{1/2}\right] ;$$

$$x = \frac{E'}{B} ;$$

E' = total kinetic energy of the system with respect to c.m. coordinates;

$B = \frac{z\,Z\,e^2}{R} = \frac{0.960\, z\, Z}{A^{1/3}}$ = barrier height.

The penetrability function thus calculated is with respect to the center of mass, and therefore its effect must be added to the reaction threshold E_{01} to find the incident particle energy in laboratory coordinates for a given penetrability factor.

$$E_{01} = -Q\,\frac{(A_1 + A_T)}{A_T} \qquad (7)$$

Q = energy of the reaction,

A_1 = mass number of the neutron,

A_T = mass number of the target nucleus.

It was decided to use phosphorus^{31} and aluminum^{27} for detection of fast neutrons in these experiments. $P^{31}(n,p)Si^{31}$ has a threshold of 3.9 Mev calculated by equations (6) and (7) for 0.5 penetration probability, and leads to a 170-minute beta activity in Si^{31}. Similarly, $Al^{27}(n,p)Mg^{27}$ has a threshold of 4.6 Mev for 0.5 penetra-

tion probability, and has a 10.2-minute daughter. Both these elements have appreciable thermal activation cross sections, and to prevent such thermal activations, the foils were irradiated in cadmium holders.

Experimental Foil Procedures

The indium foils used in these experiments were the same foils used by Tittle[1], Dacey, Paine, and Goodman[5], and Delano[6]. They were cut from sheets supplied by the Indium Corporation of America and guaranteed to be of 99.97% purity. The sheets were hand-rolled to a thickness of 0.003 inch, or about 56 mg/cm^2. The foils were die-cut to a diameter of 3 cm and carefully weighed. These foils were calibrated by Tittle[1], and his calibration factors, which are tabulated in Tables 2 and 3 of Dacey, Paine, and Goodman[5], were used throughout this work.

The aluminum foils were those used by Delano and Goodman[6]. They had been cut with 1 3/16-inch dies from 99.8% pure 0.024-inch thick aluminum sheet. The phosphorus foils were made from 1/16-inch thick, 1 3/16-inch diameter lucite rings filled with ACS powdered red phosphorus and covered on both sides with Scotch tape. These foils were considered to be "thick" to the beta rays emitted, and no corrections were made for the slight variations in mass between the foils.

The foils were counted on the counters used by Tittle[1], by Dacey, Paine, and Goodman[5], and by Delano and Goodman[6] (see Figure 6). These counters consisted of two Victoreen mica window beta counters (Model VG-Special) mounted in cylindrical lead shields. Pulses

from the counters were fed into two standard amplifiers and scales-of-sixty-four. An electric timer operated the counters on a cycle of: one minute off, five minutes on, one minute off, five minutes on.

Delano[6] determined the counters to be linear beyond 20,000 counts per minute. No counting above 10,000 counts per minute was attempted in these experiments, and generally counting was done below 5,000 per minute. Hence no corrections for counter dead time were necessary.

Counter No. 1 had a slightly higher sensitivity than counter 2. This was corrected by computing a counting ratio according to the following equation:

$$\frac{C_{11} \cdot C_{12}}{C_{22} \cdot C_{21}} = R^2$$

where

C_{11} = activity of foil 1 in counter 1,

C_{22} = activity of foil 2 in counter 2,

C_{12} = activity of foil 2 in counter 1,

C_{21} = activity of foil 1 in counter 2,

R = counting ratio between the counters for equal foil activities.

By the simple expedient of counting two foils simultaneously in the two counters, and switching the foils between the counters, a counting ratio of 1.048 was determined to well within one-half of one per cent accuracy.

In an attenuation experiment, the foil holders were suspended within the ducts by Scotch tape from a small wire ring which was allowed to spring out tightly against the duct walls (see Figure 7). The phosphorus or aluminum foils were located at the axis of the duct. The cadmium-covered indium foil and the aluminum-covered indium foil for one position within the duct were located equally distant from the duct axis, the assumption being made that if there were a flux gradient across the duct, it would vary symmetrically about the axis of the duct.

With the foils in place and the door closed, the cyclotron was operated for five to thirty minutes. An attempt was made to irradiate the foils farthest from the source sufficiently to get statistically significant counting rates without activating the foils nearest the cyclotron to such a degree that unusual delays were required before these foils could be counted.

After irradiation, the foils were removed from the ducts and counted, the least active being counted first. Indium foils were counted five minutes on the front and five minutes on the back, the sum being considered as proportional to the flux. Aluminum foils and phosphorus foils were counted only on the front, the assumption being made that these foils were so transparent to fast neutrons that no important difference would be found between the front activity and the back activity.

The activity for each foil was corrected to the end of the activation. Corrections were made for counter counting ratios, for cadmium attenuation, and for individual foil calibration in accordance with Tables 2 and 3, page 19, Dacey, Paine, and Goodman[5]. The resultant activities were then considered to be proportional to the neutron flux at the foil location.

Although in these experiments the important consideration was the relative flux at different points and not absolute values, some idea of absolute fluxes may be obtained from the calibration of the foils against a known flux by Dacey, Paine, and Goodman[5].

Gamma Ray Detection Methods

Gamma ray measurements were attempted within the duct using a standard Victoreen Model 1B85 Thyrode Geiger tube and an amplifier-scaler. The flux was so high that even at the outlet of the bent duct, the counting rate blocked the scaler. A second attempt was made using a smaller Victoreen Geiger tube Model 1B87/VXC-11. This tube has a sensitive volume of less than 1/10 cubic inch. Even when enclosed in a shield of 2 1/2 inches of lead, the counting rate was so high that accurate readings could be obtained over only the last few feet of the duct.

Acceptable gamma measurements were finally obtained using a fish pole ionization chamber monitor made by the M.I.T. Health Physics Group headed by Samuel Levin. This ionization chamber used a simple monitoring circuit developed by the Clinton Laboratories, and was calibrated with standard radium sources before measurements in the ducts were begun.

In all gamma measurements reported herein, the distance along the duct axis is considered to be the distance from the entrance of the duct to the mid-point of the ionization chamber. It is realized that this introduces an error due to the finite size of the chamber, but since the relative gamma intensities at any point, and

not the absolute intensities, were considered important, this error can be neglected.

III. RESULTS AND DISCUSSION

Attenuation in Solid Shield

To understand the effects of ducts within shields, it is necessary to know the attenuation of radiation in a solid shield. Delano and Goodman[6] investigated the M.I.T. cyclotron shield and obtained attenuation lengths* of 28.5 cms for both thermal and indium resonance neutrons (see reference 6, Figures 14 and 15).

The results of Delano and Goodman were not directly applicable to the shield wall in which the present ducting experiments were conducted, however, since their investigations were in the wall situated 90° to that in which the ducts were located. The bore hole in which their measurements were made was located about 21.7° from the axis of the deuteron path where it strikes the target, or well within the cone of primary neutrons. The spectrum undoubtedly was harder than in the present ducting experiments.

In order to obtain the neutron attenuation in the wall in which the ducts were located, a similar experiment was conducted in which the straight duct was filled with concrete plugs of composition equivalent to

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*In this discussion, attenuation length is taken as the distance in which the radiation undergoes a reduction by a factor of ten.

that of the duct blocks themselves. The neutron distribution through the resulting essentially solid shield is shown in Figure 10. The attenuation length for indium resonance neutrons is about 19 cms and the attenuation length for thermal neutrons is only slightly larger, i.e., 20.4 cms. Although the observed curve of neutron attenuation is nearly linear, there is a slight upward curvature in contrast to Delano and Goodman's results. The larger attenuation lengths observed by the latter probably result from the higher energy neutrons. Presumably the upward curvature in the present curves results from the hardening of the spectrum as one moves into the shield. It is unclear why a similar curvature was not observed by Delano and Goodman.

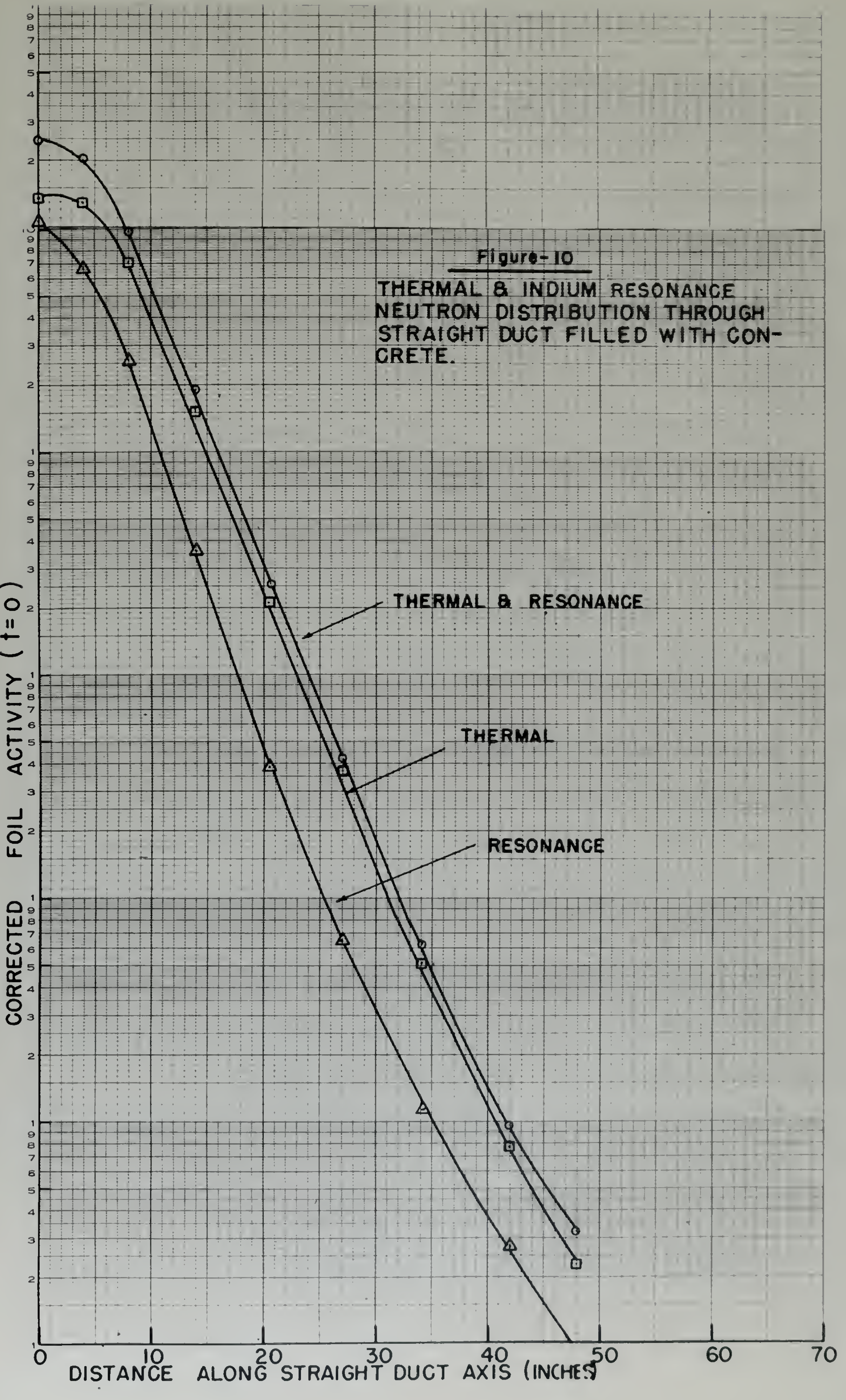

Figure-10

THERMAL & INDIUM RESONANCE NEUTRON DISTRIBUTION THROUGH STRAIGHT DUCT FILLED WITH CONCRETE.

EUGENE DIETZGEN CO.
MADE IN U.S.A.
NO. 340-L510 DIETZGEN GRAPH PAPER
SEMI-LOGARITHMIC
5 CYCLES x 10 DIVISIONS PER INCH

Theoretical Considerations of the Effects of Ducts in Shields

At any point within a duct it is convenient to consider the neutron flux at a given energy as made up of three components. The first component, hereafter called the "direct" component, is made up of those neutrons which are incident on the duct opening and are transmitted directly through any straight section of the duct from any source without striking the duct walls or passing through the shield material. Another way of describing this direct component is to consider it as composed of those neutrons which would be present in a duct in a shield material which is perfectly opaque to neutrons and has a zero scattering cross section.

The second, or "transmitted," component consists of those neutrons which are incident upon the walls surrounding the duct opening, penetrate the shield material, and are scattered into the duct somewhere along its length. Otherwise stated, this component consists in entirety of all neutrons not incident directly upon the duct opening but which are later found within the duct.

The third, or "scattered," component is made up of those neutrons which pass through the duct opening and are scattered one or more times from the duct walls as they proceed down the duct. This component can be considered to be the "streamed" or "canalized" component.

To a good first approximation, the transmitted component is given by the flux in solid concrete as shown in Figure 10, except for the first few inches of the duct. In other words, the flux of neutrons which is transmitted through the shield material to a foil located at, for example, thirty inches from the entrance of the straight duct, is almost exactly the flux which is found at thirty inches in a solid shield with the same incident flux and spectrum. This ignores the small contribution from the neutrons incident on the plug at the entrance.

The scattered component is not susceptible of direct calculation or experimental determination, but it may be obtained by subtracting the transmitted plus direct components from the total obtained from direct experiment. This has been done and plotted in Figure 11 for resonance neutrons in the six-inch straight duct in concrete. The scattered component, except over the first few inches of the duct, is almost exactly exponential in form, and is the major contribution to the total flux over the entire length of the duct beyond nine inches. The direct component, on the other hand, is less than twenty per cent of the total flux except over the first six inches and the last eighteen inches. It appears from Figure 11, however, that for six-inch ducts longer than forty-eight inches in concrete the direct component would become dominant, and that it would be dominant for even

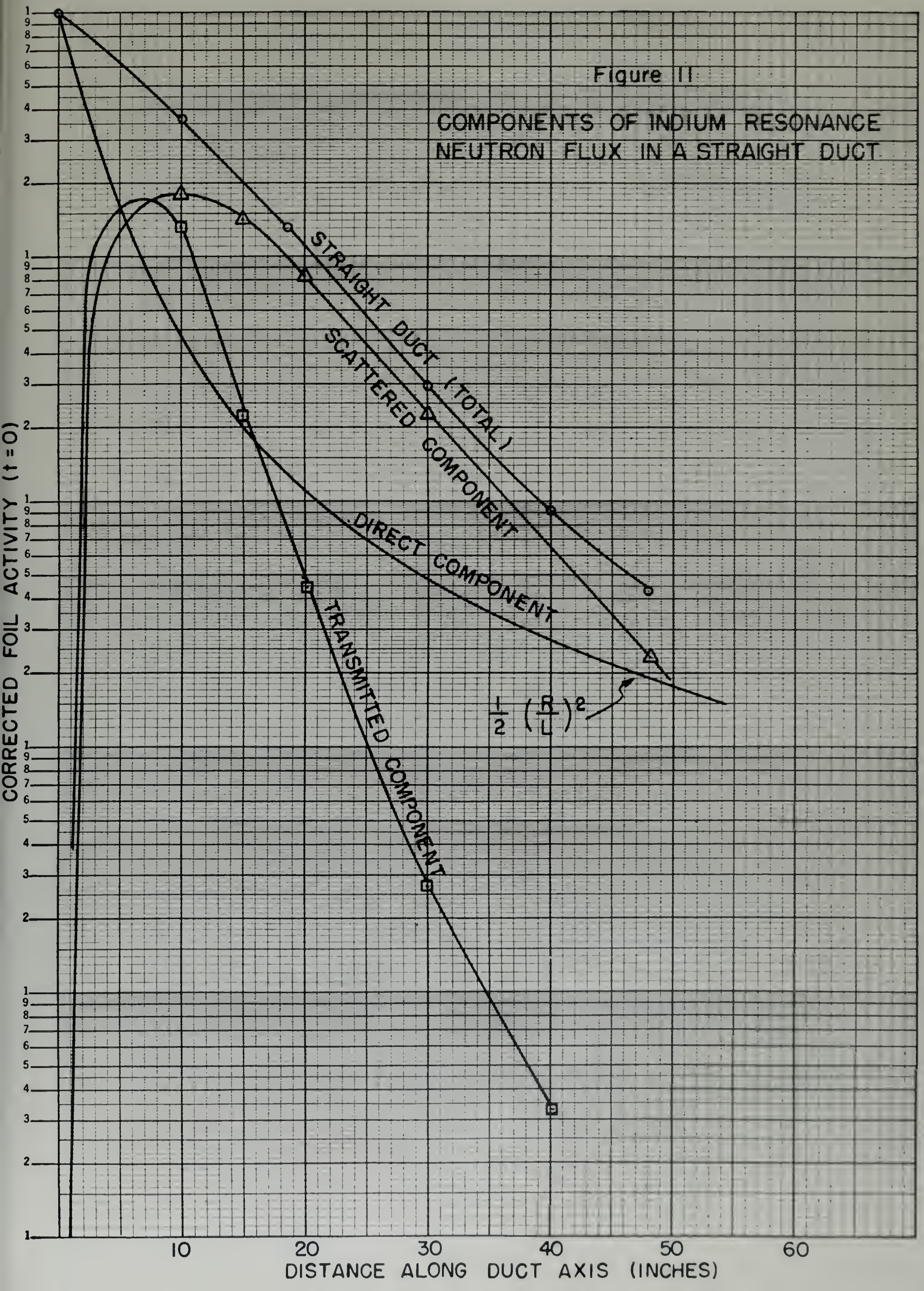

Figure 11

COMPONENTS OF INDIUM RESONANCE NEUTRON FLUX IN A STRAIGHT DUCT

shorter ducts if they were of a diameter smaller than six inches.

These three components are shown schematically for a straight duct in Figure 10-a.

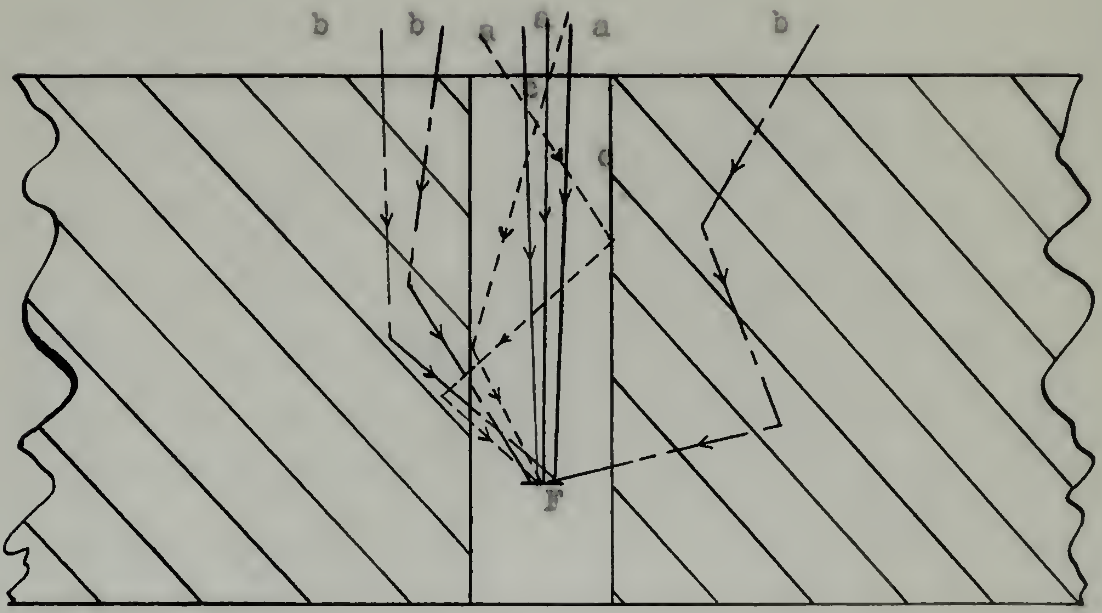

Figure 10-a

(a) ———————— = direct component

(b) ——— - - ——— -= transmitted component

(c) - - - - - - - - -= scattered component

F = foil

The direct component of the flux within a duct is susceptible to direct mathematical derivation as follows:

Assume a plane isotropic source of neutrons at the entrance to a straight duct of radius r in a completely neutron opaque non-scattering shield material. (The assumption of a plane isotropic source is believed to be a good one for the present investigations.) Consider the activation of a foil at the duct entrance A and at B a distance ℓ within the duct.

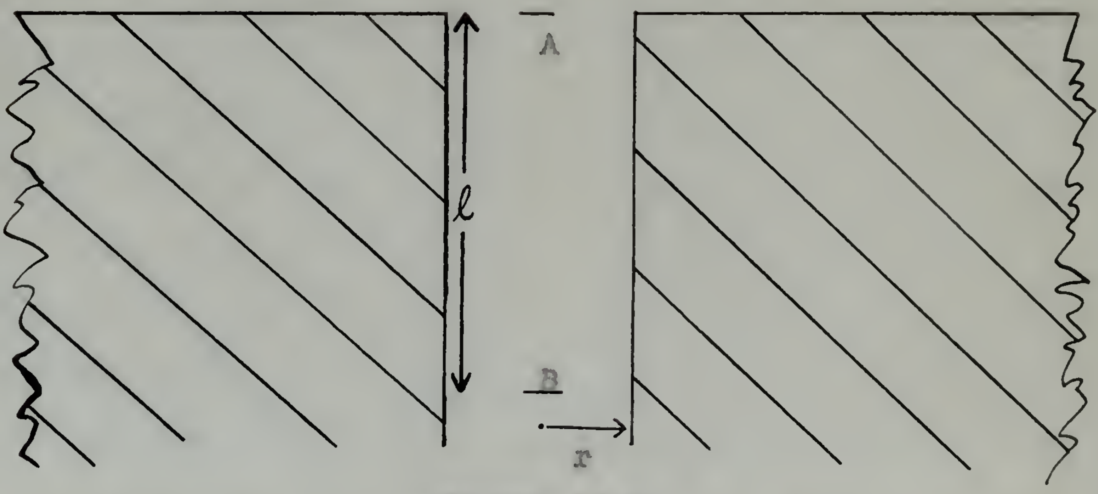

Figure 10-b

Assume the foil at A is activated to an activity A_o and the foil at B to an activity A_1 which is related to A_o by the ratio of the area of the duct opening to that of the hemisphere of radius ℓ:

$$\frac{A}{A_o} = \frac{\pi r^2}{\frac{1}{2} \cdot 4\pi \ell^2} = 1/2 \, \frac{r^2}{\ell^2} \qquad (6)$$

Since the direct component is not important over much of the duct length, any error in the derivation of the equation for the direct component resulting from the assumption of a plane isotropic source does not produce a significant error in the computation of the other two components.

Assuming cross sections as given by Goodman[10], the scattering cross sections for the concrete used in these experiments were 11.4 barns for thermals, 6.0 barns for indium resonance neutrons, and 1.13 barns for fast neutrons. Thus, as shown in the Appendix, one would expect that the scattered component of the fast neutron flux would experience a greater attenuation in a given length of duct than would the scattered component of the resonance or thermal neutrons, and also that the direct and scattered components of the fast neutron flux would experience greater attenuation at duct bends. This latter phenomenon is increased by the greater forwardness of the scattering of fast neutrons in the laboratory coordinates.

Discussion of Experimental Results

a. Thermal neutrons: If we apply the considerations outlined above to the curves obtained by experiment, many significant effects can be qualitatively understood. It can be seen from Figure 12 that under the particular conditions of these experiments, the attenuation of thermal neutrons in all ducts is essentially exponential. From this it would appear that the direct component never becomes over-riding for these neutrons. Since a comparison with Figure 10 for neutron flux in solid concrete indicates that this latter flux is a small fraction of the flux in the duct at the same depth from the front wall of the shield, the transmitted component is also seen to be unimportant except for the first few mean free paths in the duct. As a result, the scattered component is by far the most important over most of the duct length.

There are perturbations from the straight exponential form in the curves of Figure 12, however. The helical duct curve remains appreciably above the exponential for almost the first fifteen inches of its length. This would appear to indicate that the first, or transmitted, component is more important over the first section of the helical duct as compared with the others. In the helical duct, the first foot of duct length removes the duct only about nine inches from the face of the duct.

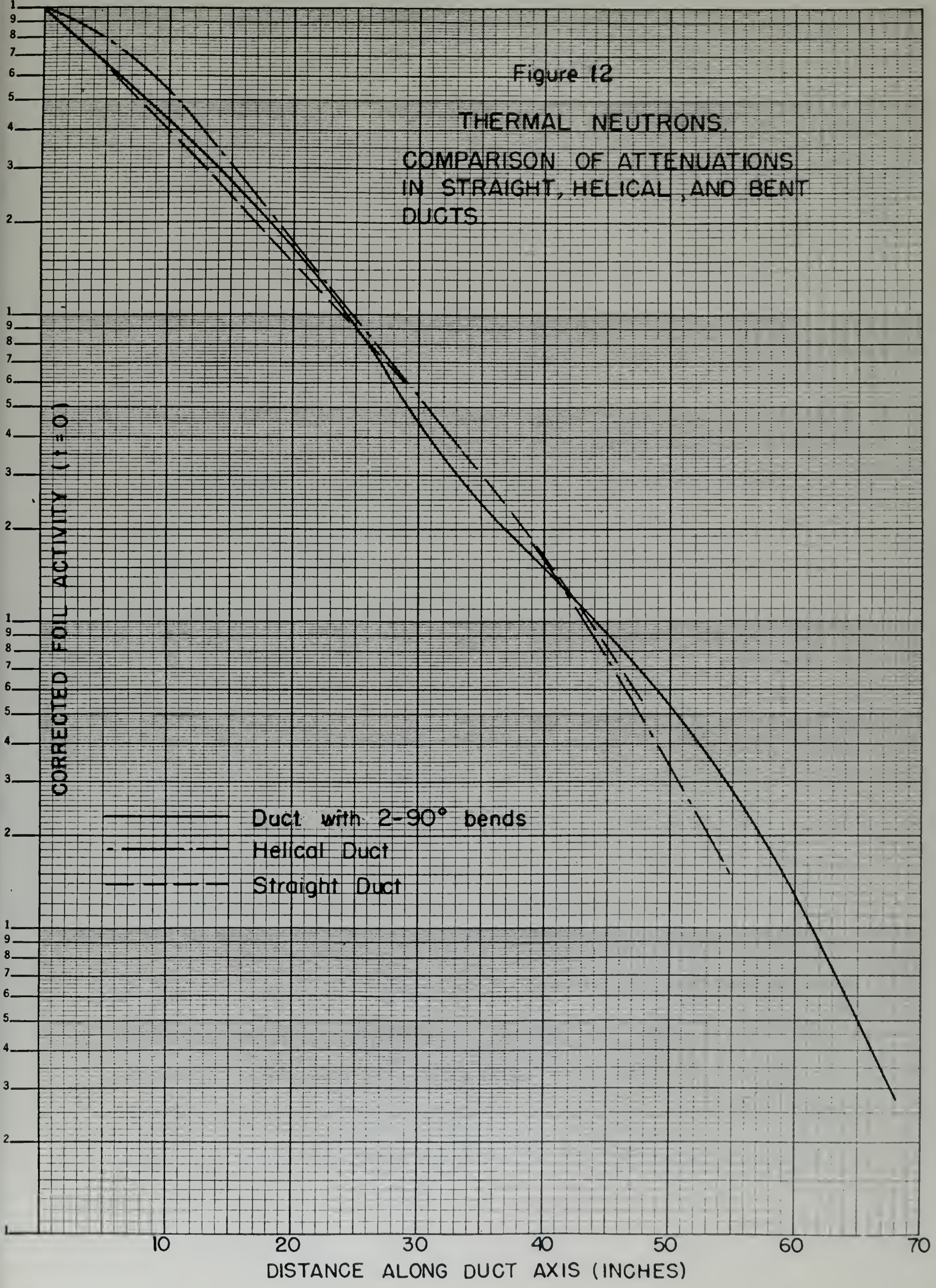

Figure 12

THERMAL NEUTRONS

COMPARISON OF ATTENUATIONS IN STRAIGHT, HELICAL, AND BENT DUCTS

In the other two ducts, the first foot of length removes the ducts twelve inches from the front face. One would expect, therefore, that there would be a higher transmitted component of thermals feeding into the duct from the concrete over the first few inches of the helical duct, especially since the curve for thermals in solid concrete, Figure 10, shows relatively high thermal intensities in this vicinity.

It may also be seen from Figures 12 and 13 that the attenuation in the duct with two right angle bends shows a marked dip downward from the exponential in the vicinity of the two bends, and that this dip is more pronounced at the first bend than at the second. This would seem to indicate that the first bend eliminates the second, or direct, component from the source, and that a given length of bent duct results in greater attenuation, even for thermal neutrons, than an equal length of a straight duct. A new direct component, originating in a virtual source on the outboard walls of the first bend, is projected down the second straight section of the duct.

The curve for the duct with two right angle bends is slightly flatter over the length between the two bends than over the rest of its length. This can be understood when one considers that over this length the first, or transmitted, component undergoes no decrease whatsoever, since the duct is parallel to the front face of

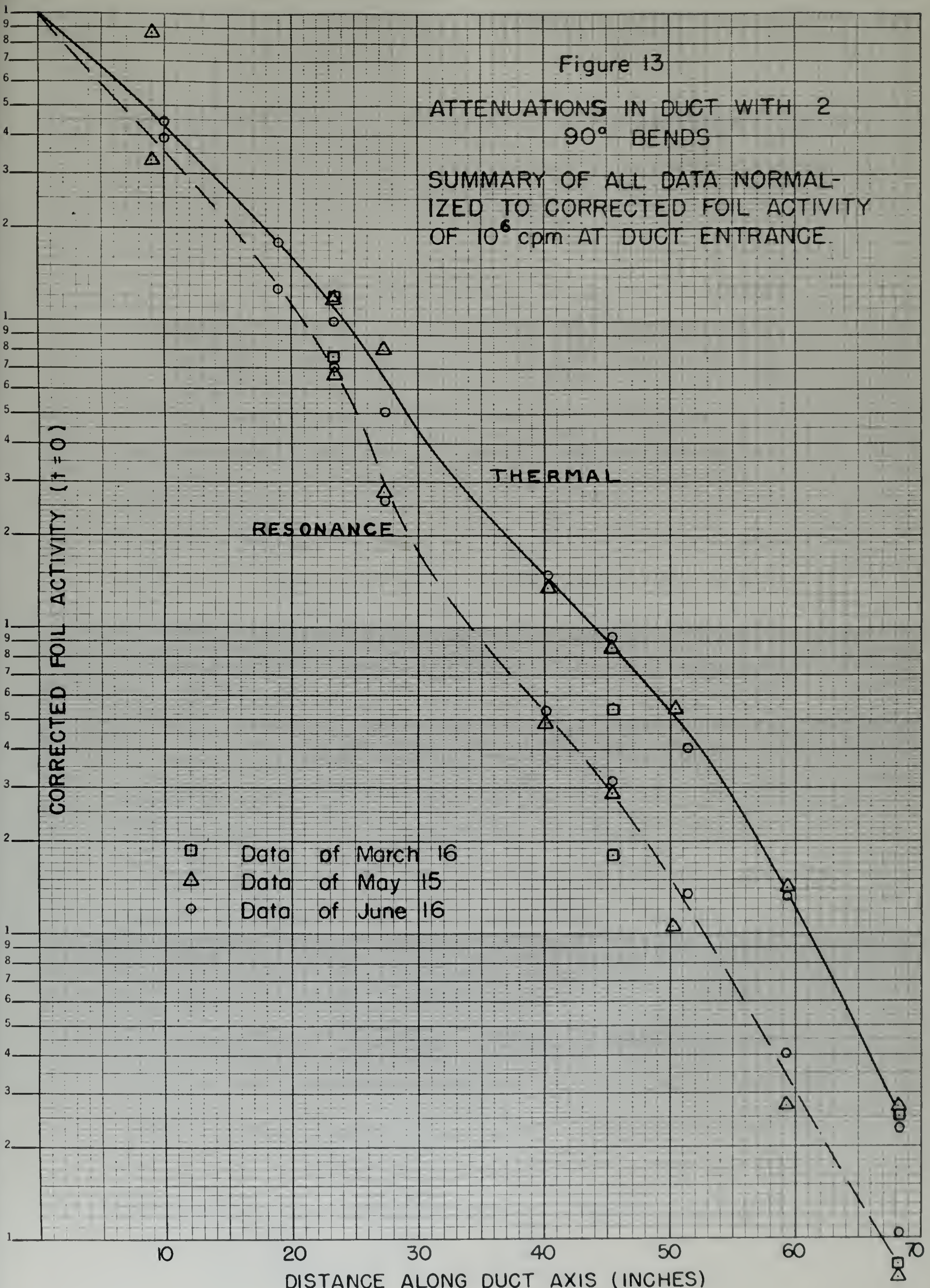

Figure 13

ATTENUATIONS IN DUCT WITH 2 90° BENDS

SUMMARY OF ALL DATA NORMALIZED TO CORRECTED FOIL ACTIVITY OF 10^6 cpm AT DUCT ENTRANCE.

the shield, whereas over the rest of the length the duct is perpendicular to the front face of the shield, and the transmitted component here is attenuated as shown in Figure 16.

All three duct curves show a slight downward trend over their last ten inches. This may be explained by pointing out that the foils at the ends of the ducts had no material behind them, and that they were, therefore, not subjected to a flux of thermal neutrons scattered back upon them by material located to their rear. In other words, the foils within the duct proper were subject to a certain amount of albedo effect from concrete farther from the front of the shield than they. The foils at the duct exits were not under this influence, and thus their readings would be expected to be lower.

Certain other experimental data seem to confirm that the amount of material remaining affects the attenuation obtained. The attenuations of thermal neutrons are compared in Figure 17 for two radically different experimental conditions. In one case only half the concrete blocks (twenty-four inches) were in place; in the other all blocks (forty-eight inches) were used. Comparison of the attenuations for those portions of both ducts within a distance of twenty-four inches from the outer face indicates identical relaxation lengths. For a given section of duct the attenuation is thus seen to depend partially on the amount of shielding material beyond that section.

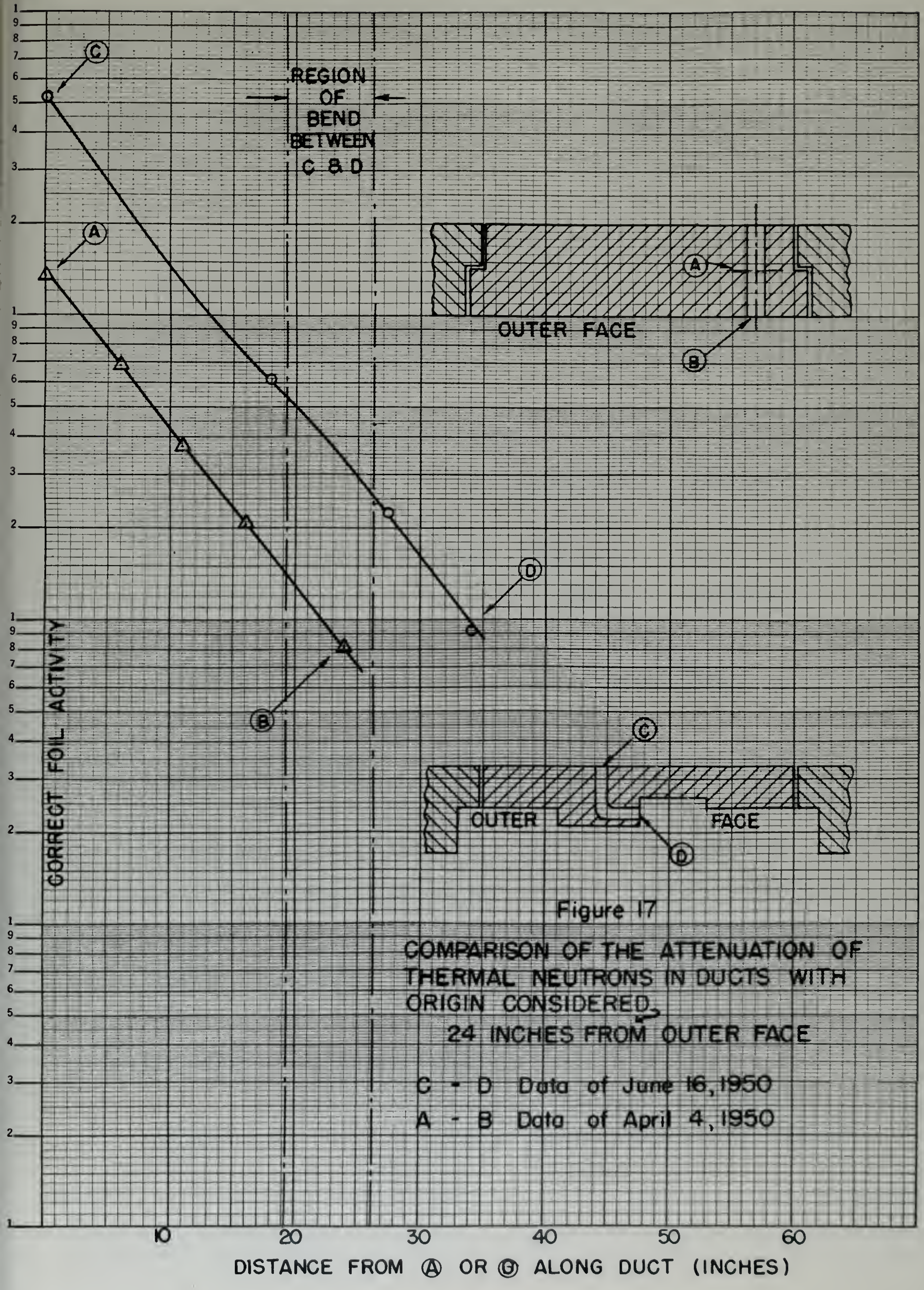

Figure 17

COMPARISON OF THE ATTENUATION OF THERMAL NEUTRONS IN DUCTS WITH ORIGIN CONSIDERED 24 INCHES FROM OUTER FACE

C - D Data of June 16, 1950

A - B Data of April 4, 1950

The attenuation of thermal neutrons in ducts of the shapes currently investigated can be summarized, therefore, as roughly exponential, with an attenuation length of approximately 50.7 cms for six-inch circular ducts in concrete, and with minor perturbations due to boundary and geometrical effects at shield surfaces and duct bends.

5. Indium resonance neutrons: The curves summarizing the results of attenuation experiments for indium resonance neutrons, Figure 14, are qualitatively similar to those for thermal neutrons, Figure 12. There are some marked quantitative differences, however. Perhaps the most obvious is that the attenuation length for resonance neutrons is considerably less than that for thermals, as can be immediately seen in Figures 13, 15, and 16. The attenuation length for resonance neutrons in all ducts was, in fact, about 44.5 cms as compared to 50.7 cms for thermal neutrons. This would seem to follow directly from considerations mentioned above of the differences in scattering cross sections for these two neutron groups, thus increasing the attenuation of the scattered component, which is dominant over the entire length, for the resonance neutrons as compared to the thermals.

Similar considerations explain the fact that the curve for the two-right-angle-bend duct has a sharper

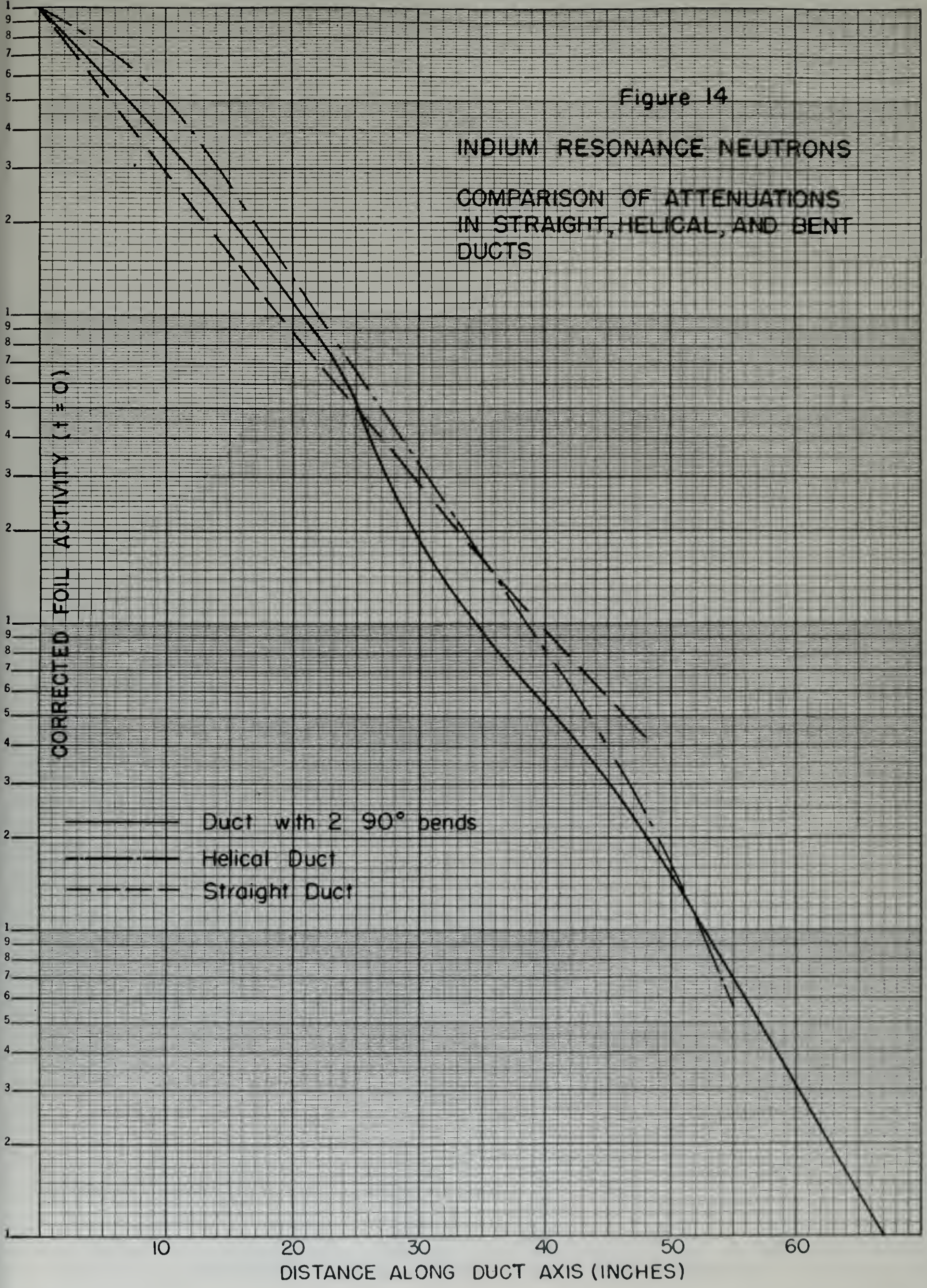

Figure 14

INDIUM RESONANCE NEUTRONS

COMPARISON OF ATTENUATIONS IN STRAIGHT, HELICAL, AND BENT DUCTS

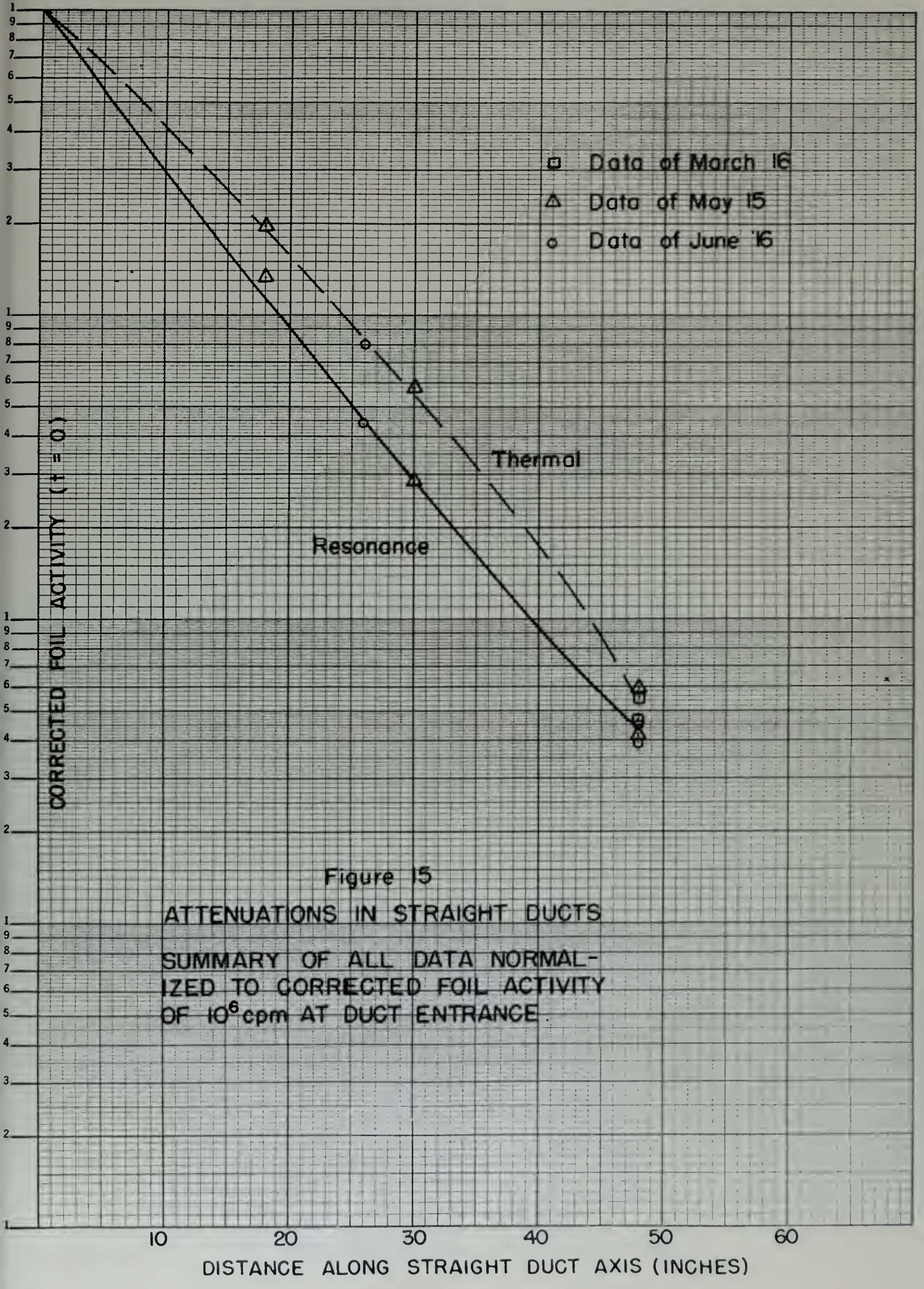

Figure 15

ATTENUATIONS IN STRAIGHT DUCTS

SUMMARY OF ALL DATA NORMALIZED TO CORRECTED FOIL ACTIVITY OF 10^6 cpm AT DUCT ENTRANCE

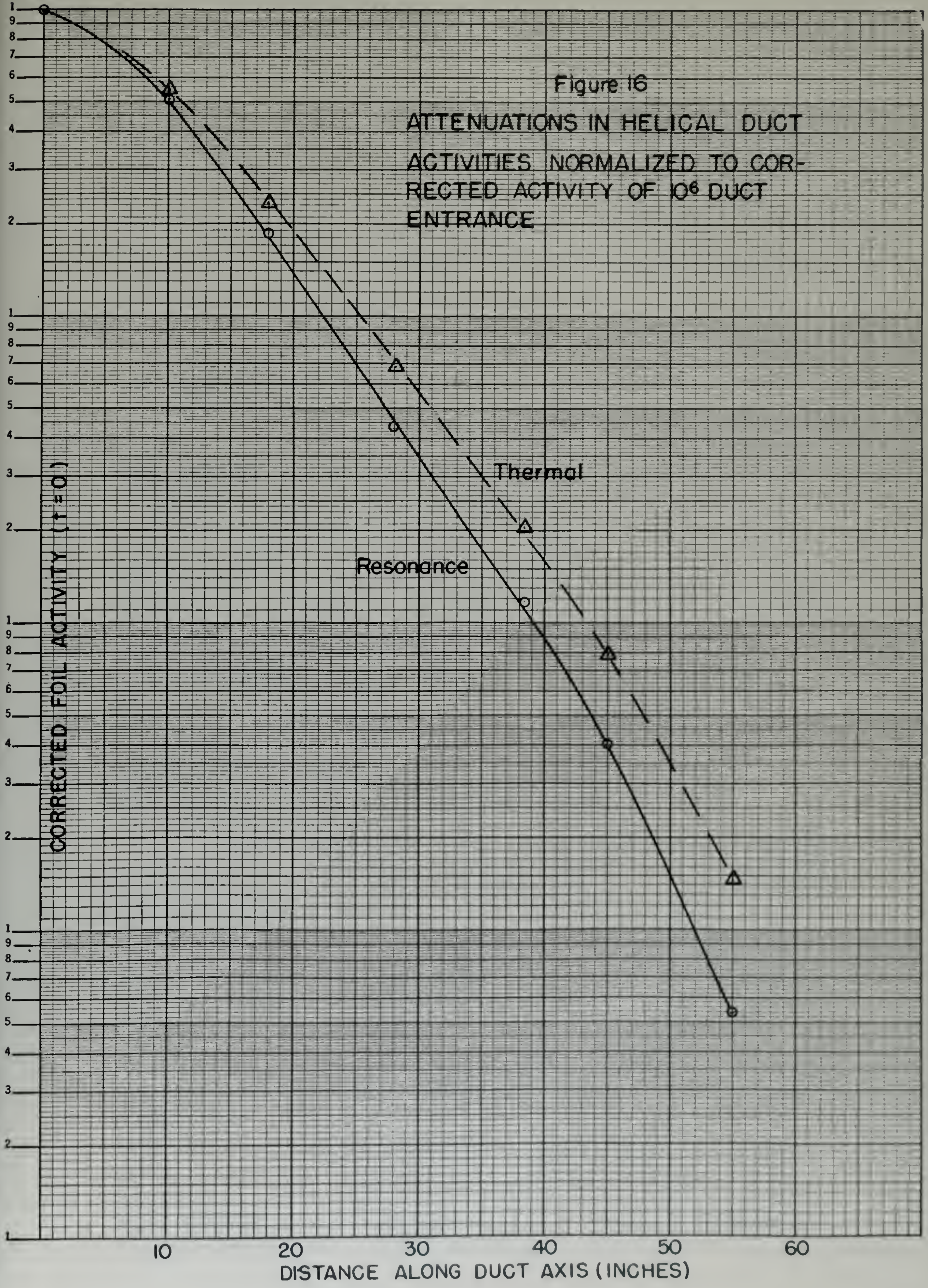

Figure 16

ATTENUATIONS IN HELICAL DUCT

ACTIVITIES NORMALIZED TO CORRECTED ACTIVITY OF 10^6 DUCT ENTRANCE

drop at the first bend for resonance than for thermals, and is flatter over the length of the middle portion, which is parallel to the front face of the shield. More resonance neutrons relative to thermals tend to continue on into the concrete at the bends rather than be scattered back into the duct beyond the bends simply because they encounter smaller scattering cross sections.

The albedo affect resulting from material behind as well as in front of the foils, mentioned in the thermal neutron discussion above as causing the slight downward trend over the last ten inches of the thermal curves, is not nearly so important for resonance neutrons since these neutrons have somewhat more "forwardness" than the thermals and thus tend to activate the foils from the forward sides only. As a result, this downward trend over the ends of the curves is not observed to so great an extent in the resonance curves.

As a matter of fact, the curves for the straight ducts for resonance neutrons actually show a slight upward trend in their last few inches. One would expect, as shown in Figure 11, that toward the end of the straight duct the scattered component would become less important as compared to the direct component. Actually, the last few inches of the straight duct is the only place where the direct component would be expected to be important. If this be true, then the upward trend of resonance neutron curves in the straight duct, as shown in Figures 14

and 15, can be understood, since the direct component has this form at this point. This effect is not obtained for the last few inches of the helical or bent ducts, because there is no direct component in these ducts beyond the first bend.

c. Fast neutrons: As explained in the third section of Chapter II, the neutrons generated in the $Be^9(d,n)$ reaction in the experimental arrangement used herein, were scattered at least once and probably several times before striking the wall in which the ducts were located. The result of this scattering was that the neutrons in that part of the spectrum capable of actuating either aluminum or phosphorus foil threshold detectors was not intense, and it proved difficult to obtain statistically significant results very far into the ducts. The difficulty was increased by breakdown of the cyclotron for a target box change which resulted in a beam current of deuterons less than half that obtained before the change was made. With phosphorus foils and three-hour irradiation runs, however, it was possible to obtain fairly good results at least through the second bend of the bent duct. These results are plotted on Figure 19.

It is immediately apparent that the attenuation length for fast neutrons in the ducts was considerably less than that for the resonance and thermals, and was in fact only 25.4 cms over that portion of the curve which approaches the true exponential.

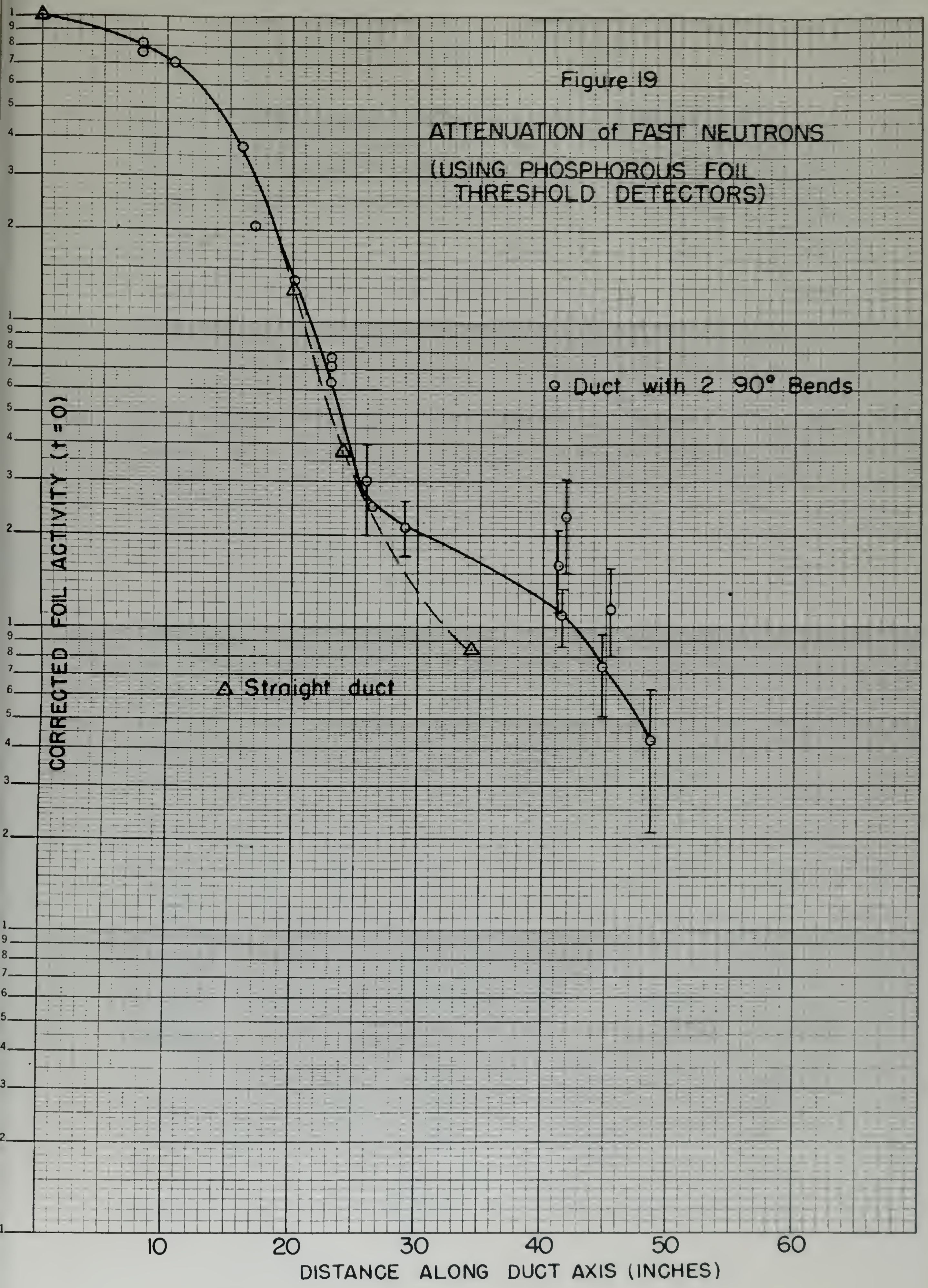

Figure 19

ATTENUATION of FAST NEUTRONS (USING PHOSPHOROUS FOIL THRESHOLD DETECTORS)

The curve for fast neutrons, however, departs much farther from the exponential over its entire length than do any of the others. The first departure, markedly upward, is in the first few inches of the duct. This is believed to be due almost entirely to the very high contribution of the transmitted component in this position which results from the long mean free path for fast neutrons in solid concrete as compared to thermals and resonance. In other words, for fast neutrons, the transmitted component appears to dominate for the first ten inches of the duct length.

The fast neutron curve is flatter than the others between the bends of the bent duct. This is due to two complimentary factors: the very much less scattering cross section for fast neutrons, which decreases the scattered component at the first bend, and the greater mean free path for fast neutrons in concrete which permits the transmitted component to become more intense with respect to the others. The result is that the transmitted component is dominant over the section of the bent duct between the bends, and since this component is constant over this distance, relatively little attenuation is obtained.

The breaks in the fast neutron curve at the bends are much sharper than those in the thermal and resonance curves at the same points. This, again, is explained by the consideration that the scattering cross

section of concrete for fast neutrons is considerably less than for neutrons of less energy, and that fast neutrons in collision with a scattering nucleus have greater forwardness in laboratory coordinates. These fast neutrons tend, therefore, to continue on into the walls instead of scattering back into the ducts or bends.

d. Neutron distributions around a straight duct: Considering the ultimate function of a shield, it is important to determine the effect of ducts on the total number of neutrons which penetrate the shield. In addition to the neutron flux intensity from the duct proper, it is necessary to know the radial distribution over the face of the shield around the duct outlet. The effect of the duct can then be determined by summing up the contributions of all elements of area around the duct and adding them to the contribution of the duct proper.

To obtain the distribution around the duct exit, foils were arranged radially around the outlet of the straight duct. The resulting distributions are shown in Figure 21. Both the thermal and the indium resonance neutron flux decrease rapidly with increasing distance from the edge of the duct. In spite of this, however, the total contribution to the resonance flux of the area within four inches of the duct edges is fifty per cent of that of the duct proper.

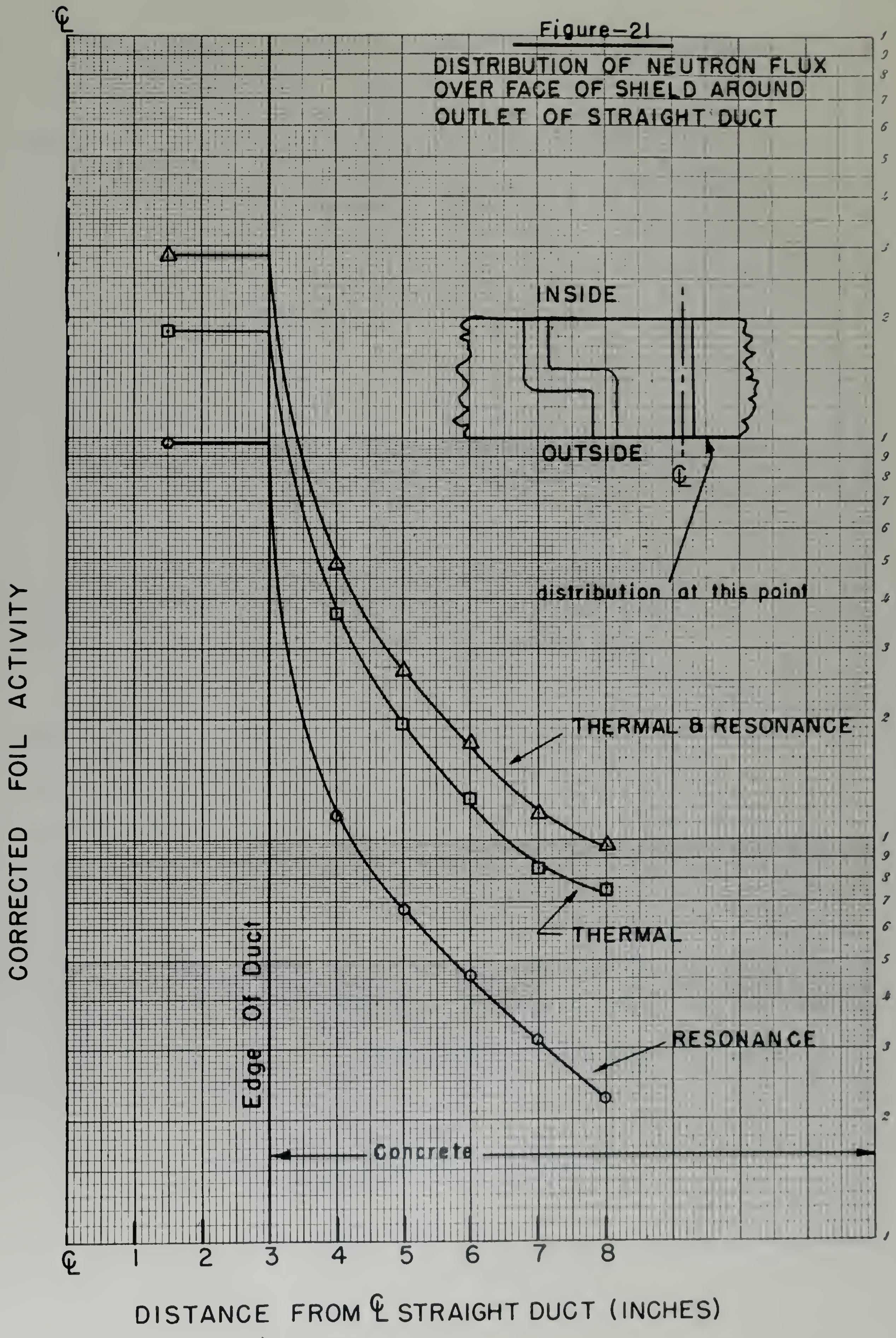

Figure-21

DISTRIBUTION OF NEUTRON FLUX OVER FACE OF SHIELD AROUND OUTLET OF STRAIGHT DUCT

Because of the complex nature of the boundary conditions at the duct exit a similar study was made in the vicinity of the mid-point of the straight duct. Foils were again distributed radially around the duct axis over the interface between two blocks. The resulting radial distributions are as shown in Figure 22. The decrease of both thermal and indium resonance neutron flux is exponential over a distance of nine inches from the duct edge. Beyond this distance a decrease in the slope of both curves is observed. Since at large distances from the duct the neutron flux would be expected to become constant, this change in slope may represent the beginning of the transition between the regions of exponential decrease and that of constant flux.

The attenuation length for thermal neutrons was determined by the latter experiment to be 27.9 cms. This compared favorably with an average value of 26.5 cms determined from the attenuation of thermal neutrons in the straight duct filled with concrete.

The neutron distributions in the shield around the duct suggest that the effect of ducts may be strongly affected by the composition of the shield. This is in agreement with the early experiments of Chalmers[11] on the canalization of neutrons.

e. The effect of voids: The theoretical study of

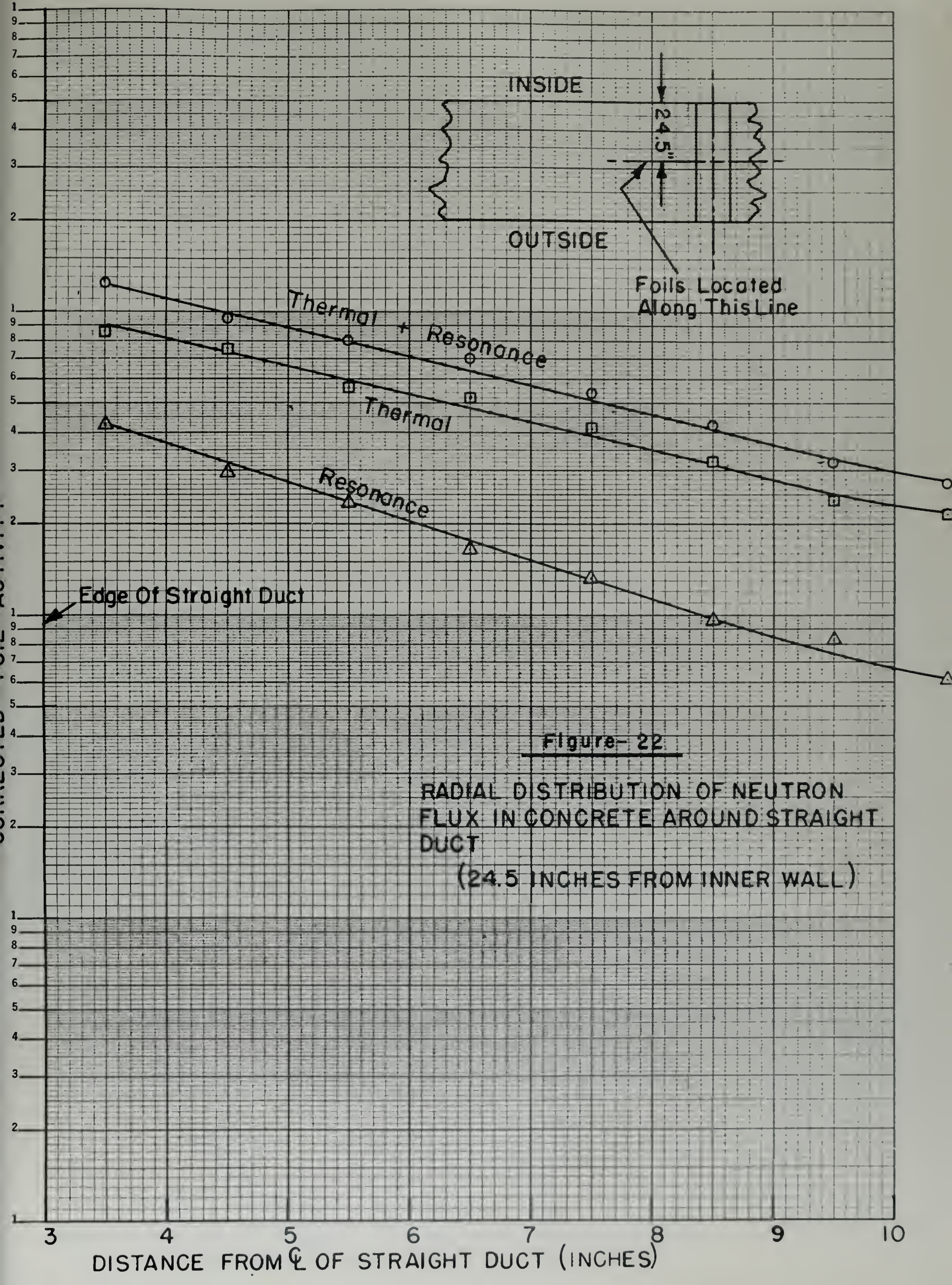

Figure- 22

RADIAL DISTRIBUTION OF NEUTRON FLUX IN CONCRETE AROUND STRAIGHT DUCT
(24.5 INCHES FROM INNER WALL)

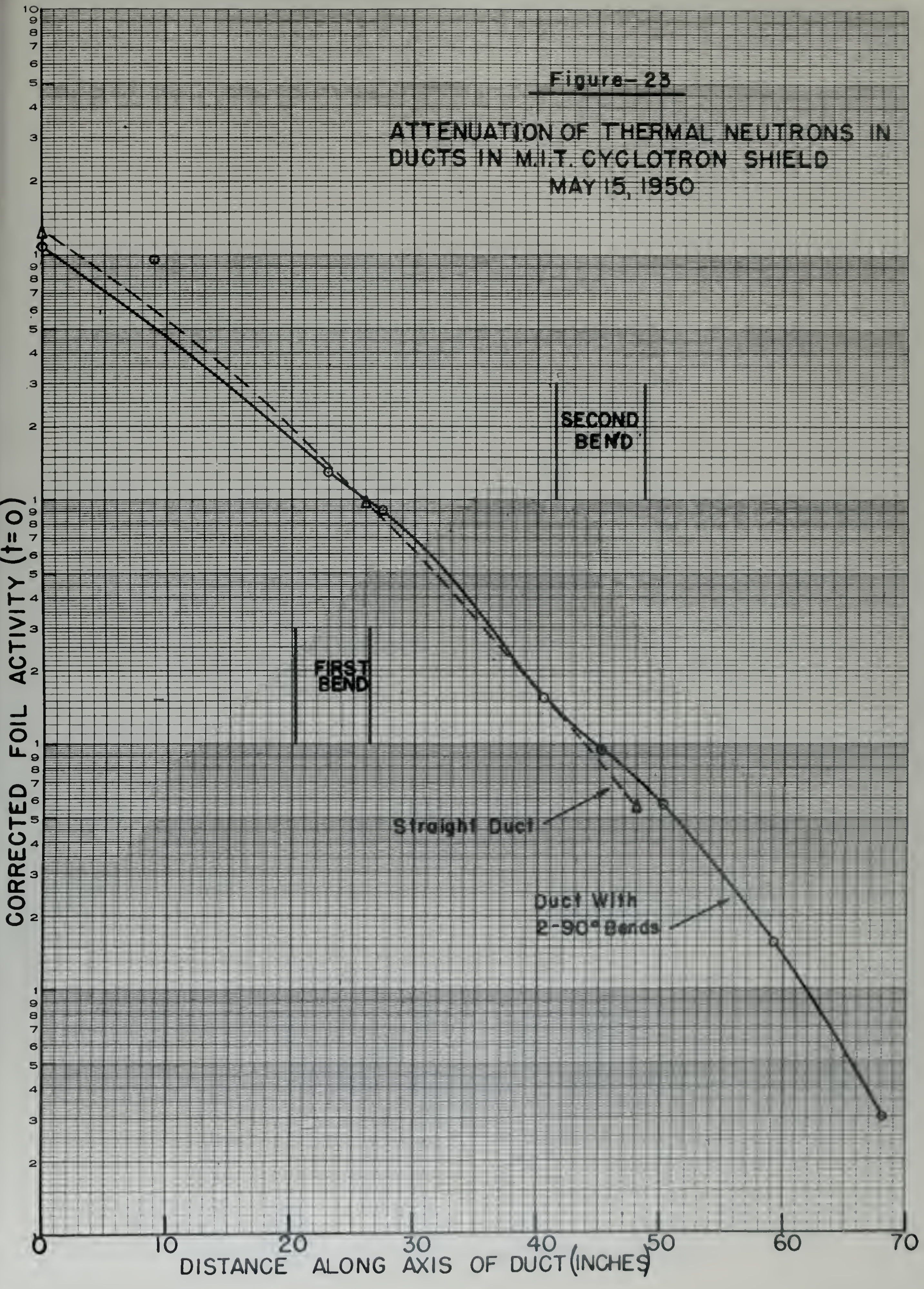

Figure- 23

ATTENUATION OF THERMAL NEUTRONS IN DUCTS IN M.I.T. CYCLOTRON SHIELD
MAY 15, 1950

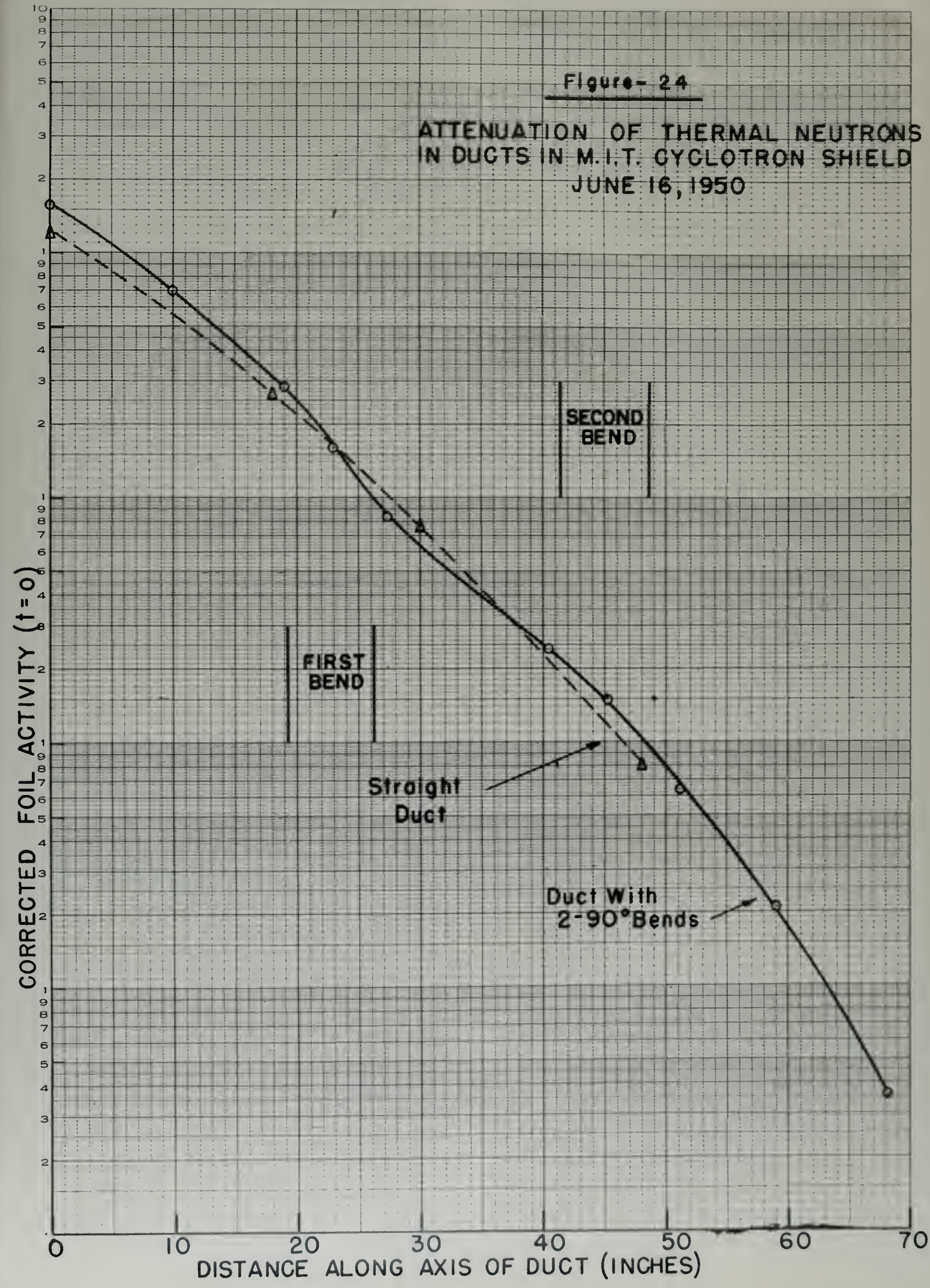

Figure- 24

ATTENUATION OF THERMAL NEUTRONS IN DUCTS IN M.I.T. CYCLOTRON SHIELD JUNE 16, 1950

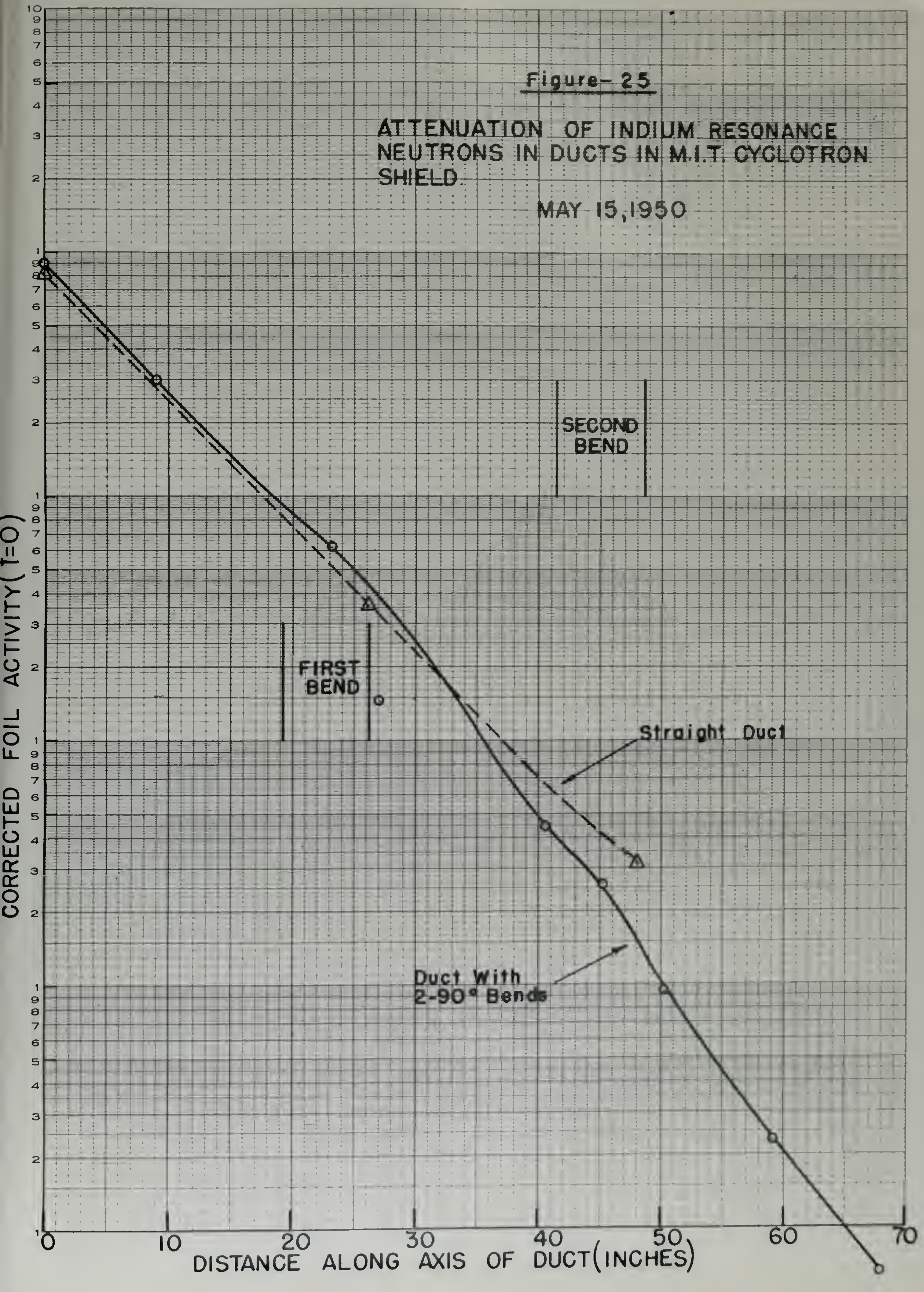

Figure- 25

ATTENUATION OF INDIUM RESONANCE NEUTRONS IN DUCTS IN M.I.T. CYCLOTRON SHIELD.

MAY 15,1950

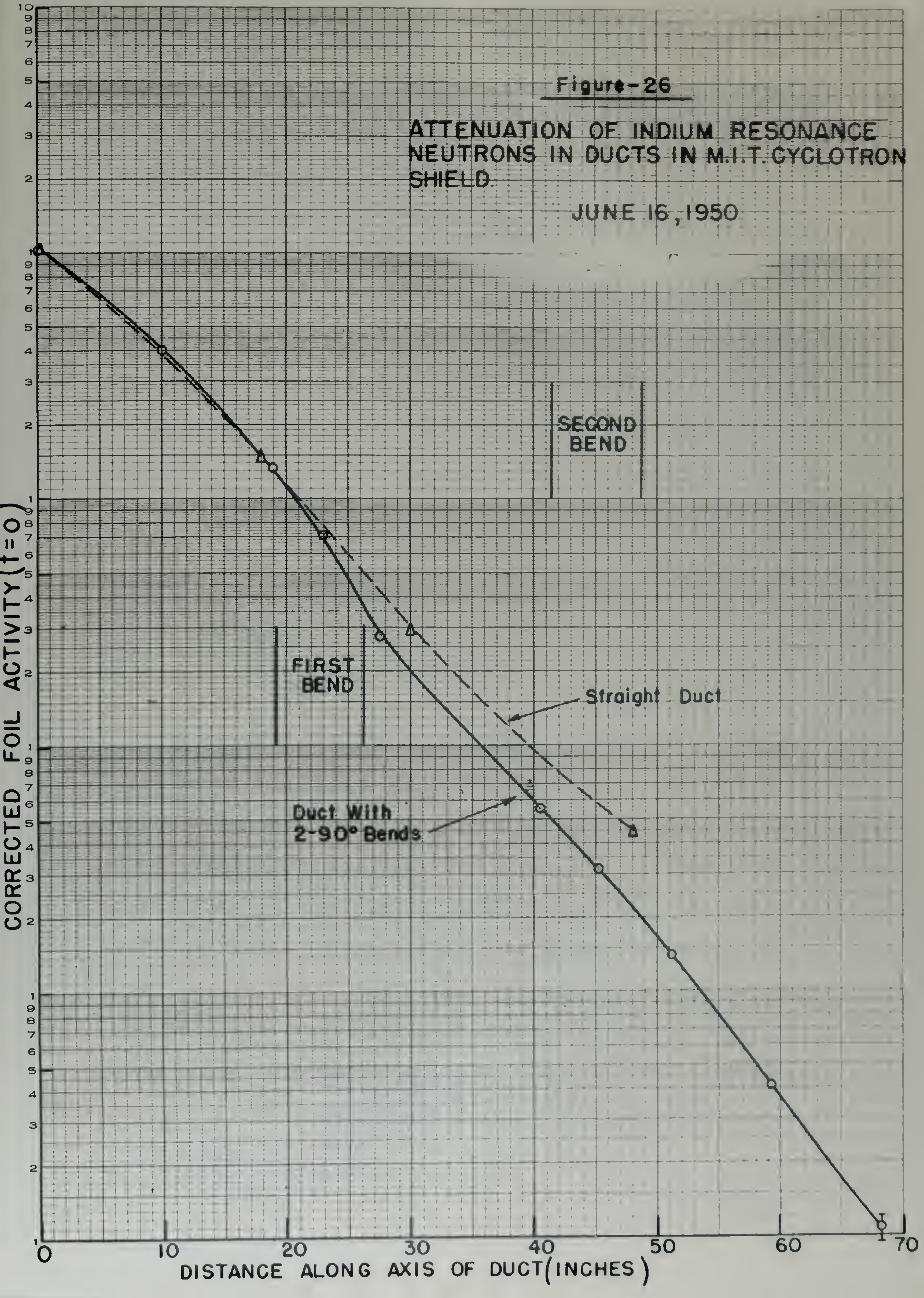

Figure-26

ATTENUATION OF INDIUM RESONANCE NEUTRONS IN DUCTS IN M.I.T. CYCLOTRON SHIELD.

JUNE 16, 1950

the effect of ducts could be explored by an investigation of the effect of voids in a shield. As a first step in such a program it was decided to study the effect of closing a straight duct by various lengths of concrete at the outer end while leaving the inner end open. Three experiments of this kind were conducted by filling the outer end of the straight duct with twelve, twenty, and thirty-six inches of concrete. In each case foils were arranged on the outer face of the shield in a radial manner with respect to the centerline of the straight duct (see Figure 8). The distributions of thermal and indium resonance neutron flux were as shown in Figures 27 and 28 respectively. Although there are indications that the distributions are Gaussian, confirmation will require the accumulation of more experimental data.

f. Neutron distributions across the ducts: It was thought not impossible that there might be a variation of neutron flux as a function of transverse position at any given point along the axis of a duct. To investigate such variations for indium resonance neutrons six small cadmium-covered indium foils were arranged in horizontal lines normal to the duct axis. Measurements were made at the mid-point and outlet of both straight and bent ducts. In each case the indium resonance flux was found within the limits of experimental error to be essentially constant across the duct.

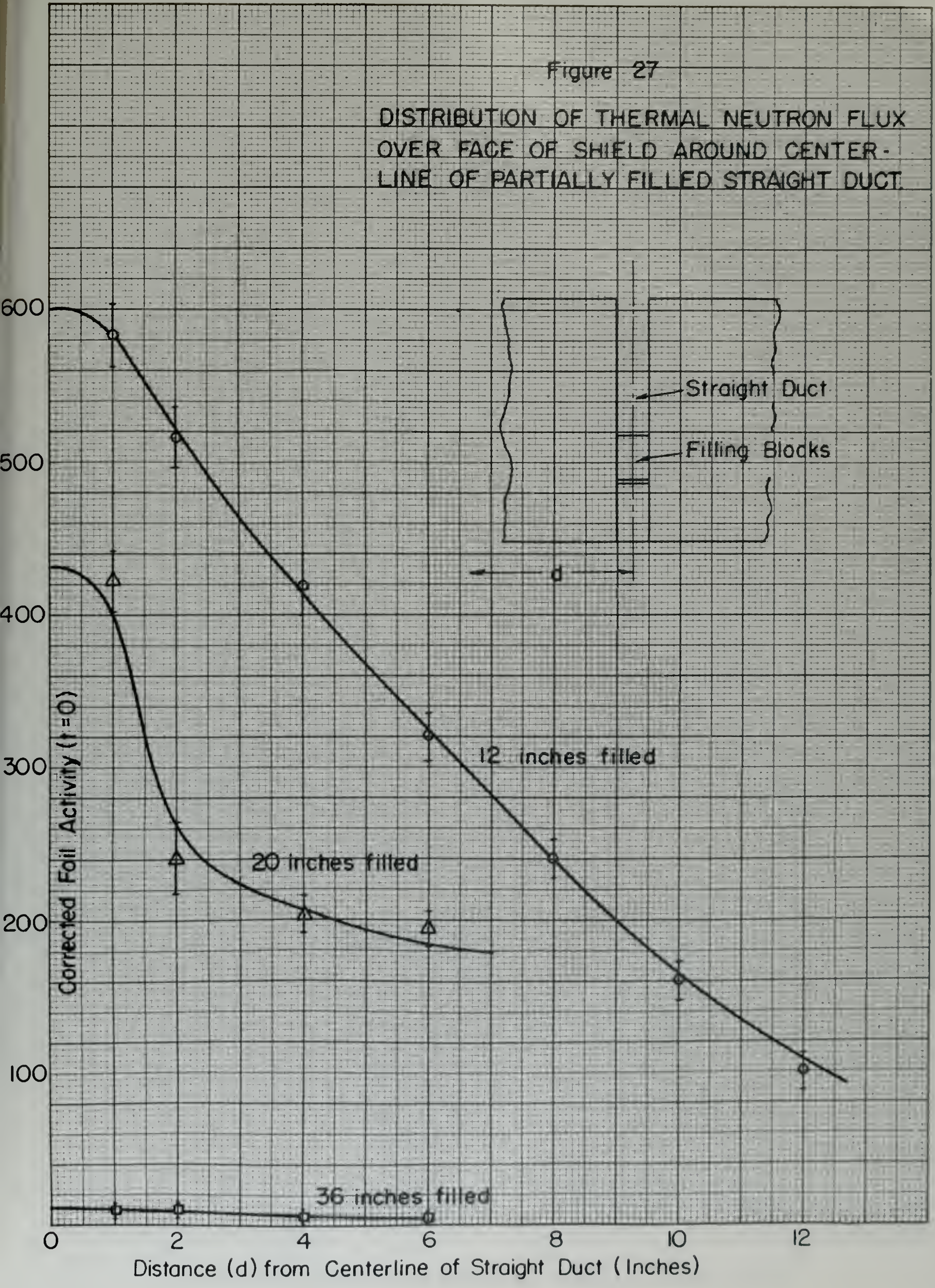

Figure 27

DISTRIBUTION OF THERMAL NEUTRON FLUX OVER FACE OF SHIELD AROUND CENTERLINE OF PARTIALLY FILLED STRAIGHT DUCT

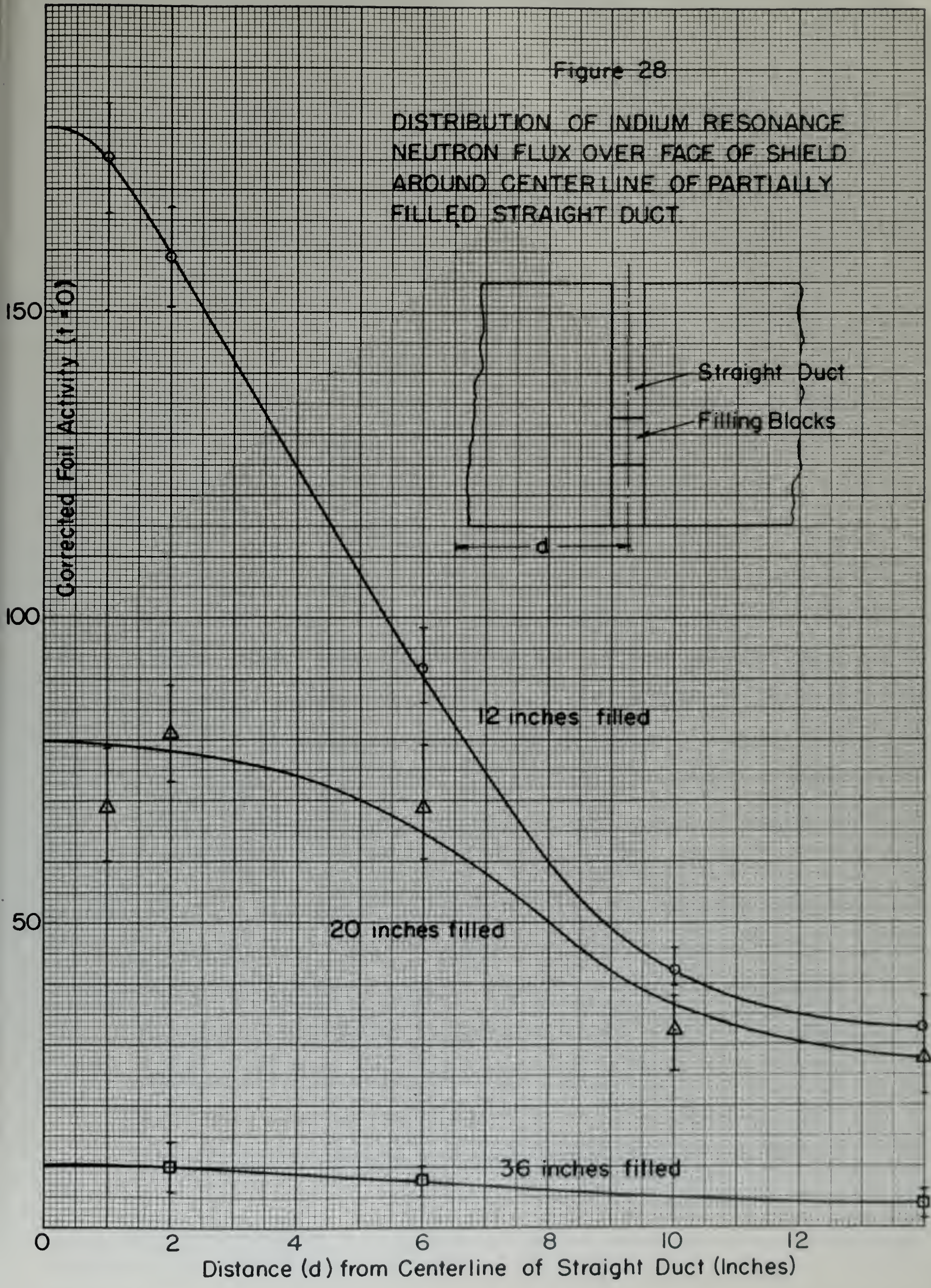

Figure 28

DISTRIBUTION OF INDIUM RESONANCE NEUTRON FLUX OVER FACE OF SHIELD AROUND CENTER LINE OF PARTIALLY FILLED STRAIGHT DUCT.

g. Gamma rays: In comparing the attenuation of gamma rays in ducts of various shapes (see Figure 28), it is evident that the overall attenuation is considerably affected by duct length. In penetrating the four feet of concrete under the conditions of the experiment, the helical duct is shown to have an effectiveness in attenuating gamma rays approximately three times that of the straight duct. Extrapolation of the results for the duct with two right angle bends suggests that it is approximately ten times as effective as the straight duct.

One important feature of the curves for both helical and bent ducts is the small value of the slope at the inner wall. As explained by Delano and Goodman[6], the gammas within the shield consist of primary gammas from the target, gammas resulting from the capture of thermal neutrons by hydrogen, and secondary gammas resulting from the interaction of fast neutrons with the shield constituents. The production of capture and secondary gammas at the inner face would seem to explain this effect.

The slope of the curve for the straight duct is generally less than the slope of the curve for either of the other two duct shapes. More particularly, its slope is less than that for the portion of the bent duct which runs parallel to the inner face. This would seem to be explained only by some component strongly affecting the straight duct and not affecting the region of the bent

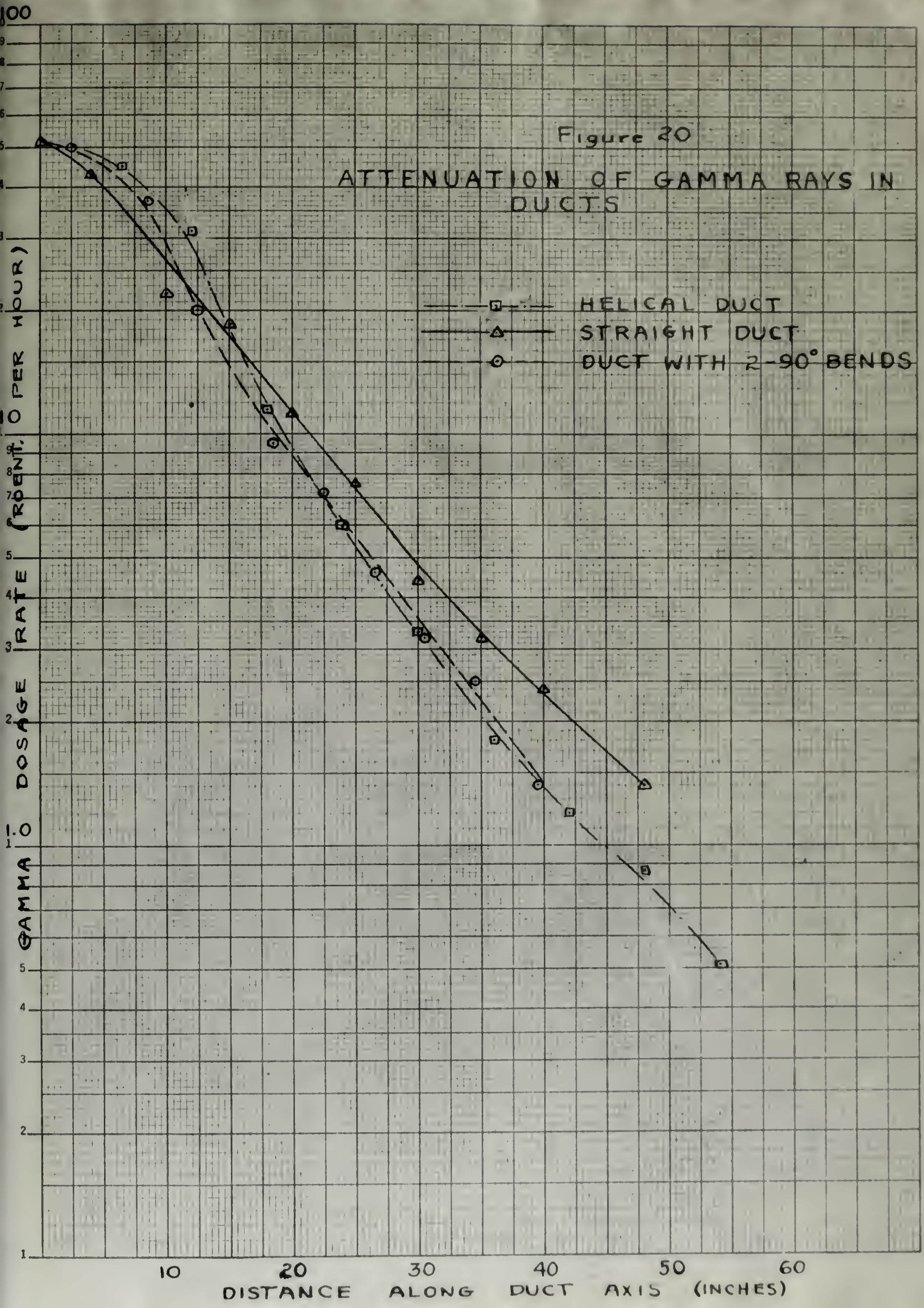

Figure 20

ATTENUATION OF GAMMA RAYS IN DUCTS

duct described above. Geometrical considerations and the continually decreasing slope of the curve for the straight duct suggest that the component in question is a direct component analogous to that already discussed for neutrons.

A further study of the attenuation of gammas in solid concrete in the region of the concrete blocks should make it possible to isolate the various components contributing to the total effects herein described.

IV. SUGGESTIONS FOR FURTHER WORK

The experiments reported herein are only the beginning if the effects of ducts in shields are to be thoroughly understood. It became apparent during the course of the present experiments that the understanding of ducts could be advanced further by experiments along the following lines:

1. An extension of the work with voids; in particular, experimentation should be carried out with the entrance portion of the straight duct plugged for various distances; that is, voids should be made in the exit of the straight duct, and the radial distribution of neutrons determined across the outer face. Experiments should also be conducted with voids of a fixed size (for example, twelve inches) located at various positions within the shield along the straight duct axis.

2. A complete survey of the face of the shield with ducts should be made. An integration of the flux over the entire area surrounding the duct as compared to an integration of the flux over the same area without a duct is the only method of determining the total number of neutrons which escape from a shield as a result of its being ducted. This number is the primary criterion in shield design.

3. The effect of ducts as a function of shield material should be determined. This would be facilitated by the use of a tank filled with water in which ducts of various shapes could be placed. Such a tank has already been fabricated to fit the M.I.T. cyclotron door in place of the blocks used in these experiments. Its use with ducts of the same size and shape as those used in the present experiments should give preliminary indications of the function of the shield material in determining the effects of ducts.

4. Duct shapes other than those investigated in the present experiments should be tested. This too should be facilitated by using the water tanks referred to above.

5. Several more exotic methods of reducing the total leakage of neutrons through ducts might be tried. Among those which the authors feel worthy of investigation are neutron traps in the form of extensions of the straight portions of bent ducts at each bend, and duct linings of materials having high cross sections for absorption of neutrons.

6. The effects of duct cross-sectional area and shape should be determined. It is possible, for example, that the aspect ratio (i.e., the ratio of the length to the width) of the cross sections of rectangular ducts may have an important bearing on the neutron atten-

uation in the duct.

7. If possible, attenuation experiments similar to those reported herein should be repeated on the straight duct with the duct length increased by one or two attenuation lengths. Such experiments should indicate much of the relative importance and absolute intensity of the direct component, since the direct component would be dominant beyond about forty-eight inches in the straight six-inch duct.

8. Attempts should be made to obtain data on fast neutrons with greater statistical significance by increasing the cyclotron beam current, or by using longer irradiation times, threshold detector foil materials with higher cross sections than that of phosphorus, or electrical counters of the hydrogen recoil type.

If these suggested experiments should be carried out, a large amount of information useful in the theoretical analysis and the intelligent engineering design of ducts through radiation shields would be obtained.

APPENDIX

Scattering Cross Sections of Concrete

In the calculations, we consider the composition of the concrete to be approximated on a weight basis by

$$H = 0.84$$

$$O = 50.9$$

$$Si = 48.3$$

The contribution of the values of $N\sigma_{sc}$ for other constituents is negligible.

Let w = weight of element per unit weight of concrete;

N = nuclei/cm^3;

σ_{sc} = scattering cross section, barns;

M = atomic weight;

A = Avogadro's number.

$$\sigma_{sc}\ (\text{concrete}) = \frac{\sum N\,\sigma_{sc}}{\sum N} = \frac{\sum w\,\frac{A}{M}\,\sigma_{sc}}{\sum w\,\frac{A}{M}}$$

Scattering Cross Sections (barns)

Element	Neutron Energy		
	.025 ev	1.44 ev	4 Mev
H	58.5	22	1.8
O	4.2	3.72	0.8
Si	2.38	2.25	1.4*

*Extrapolated value

E = 0.025 ev

$$\sigma_{sc} = \frac{.0084 \cdot 58.5 + .509 \cdot \frac{1}{16} \cdot 4.2 + .483 \cdot \frac{1}{28} \cdot 1.8}{.0084 + \frac{.509}{16} + \frac{.483}{28}}$$

$$= \frac{49.1 + 13.3 + 3.1}{.84 + 3.18 + 1.72} = \underline{\underline{11.4 \text{ barns}}}$$

E = 1.44 ev

$$\sigma_{sc} = \frac{0.84 \cdot 22 + 50.9 \cdot \frac{1}{16} \cdot 3.72 + 48.3 \cdot \frac{1}{28} \cdot 2.25}{5.74}$$

$$= \frac{18.5 + 11.8 + 3.9}{5.74} = \frac{34.2}{5.74} = \underline{\underline{6.0 \text{ barns}}}$$

E = 4 Mev

$$\sigma_{sc} = \frac{0.84 \cdot 1.8 + 50.9 \cdot \frac{1}{16} \cdot 0.8 + \frac{48.3}{28} \cdot 1.4}{5.74}$$

$$= \frac{1.51 + 2.54 + 2.42}{5.74} = \underline{\underline{1.1 \text{ barns}}}$$

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